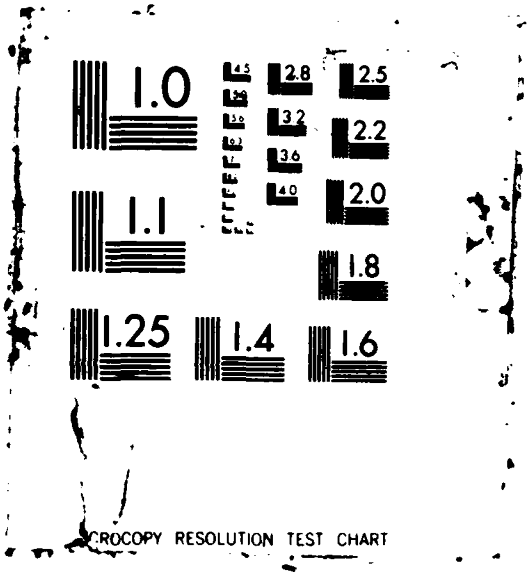
AD-A179 176 OTIS ANGB (AIR NATIONAL GUARD BASE) VISIBILITY SENSOR 1/2
FIELD TEST STUDY(U) TRANSPORTATION SYSTEMS CENTER
CAMBRIDGE MA D SCHWARTZ ET AL. FEB 87 AFGL-TR-86-0011
UNCLASSIFIED ESD-5-606 F/G 4/2 NL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AFGL-TR-86-0011

Otis ANGB Visibility Sensor Field Test Study

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D. Burnham

U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge, MA

February 1987

Final Report
Period Covered: December 1983 - January 1986

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731

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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS A179176
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; Distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFGL-TR-86-0011
6a. NAME OF PERFORMING ORGANIZATION U.S. Department of Transportation 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Geophysics Laboratory
6c. ADDRESS (City, State, and ZIP Code) Transportation Systems Center Kendall Square Cambridge, MA 02142	7b ADDRESS (City, State, and ZIP Code) Hanscom AFB Massachusetts 01731
8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER ESD-5-606
8c. ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO
63707F	2688	03	CD

11 TITLE (Include Security Classification)
Otis ANGB Visibility Sensor Field Test Study

12. PERSONAL AUTHOR(S)
D. Schwartz, D. Burnham

13a. TYPE OF REPORT	13b. TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final	FROM 12/1983 TO 1/1986	1987 February	174

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Visibility, Runway Visual Range, Automatic Observing System, Visibility Sensor, Forward Scatter Meter

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

-This study is part of a continuing effort to evaluate forward scatter meters (FSMs) for use as visibility sensors in Automatic Observing Systems (AOS) and as possible replacements for transmissometers to measure Runway Visual Range (RVR) at airports. The report analyzes data collected from three FSMs at the Otis Air National Guard Base during a 17-month period starting in 1983. Two of the FSMs use chopped incandescent light sources and have a large scatter volume. The other uses a modulated light emitting diode (LED) light source and has a small scatter volume. Two analysis procedures are included: 1) a statistical analysis of the entire data set disaggregated according to the obstruction to vision (fog, rain, snow, etc.) and the magnitude of the extinction coefficient; and 2) detailed analysis of selected reduced visibility events. Most of the time extinction coefficients measured by the FSMs and the transmissometers agreed to within 16.5 percent for RVR values between 400 and 6000 feet and within one reporting increment for AOS visibility. Most of the cases of large disagreement were traced to problems such as sensors being clogged by snow, which

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL Frederick Brousaides	22b. TELEPHONE (Include Area Code) 22c OFFICE SYMBOL AFGL/LYS

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. Abstract (Cont.)

affected both FSMs and the transmissometers. In terms of operational utility, the large volume FSMs gave more stable readings, but the FSM with the LED light source exhibited less calibration drift and greater reliability.

PREFACE

The Air Force Geophysics Laboratory (AFGL) originally developed the Forward Scatter Meter (FSM) and used it extensively as an inexpensive, low maintenance sensor for measuring visibility in various research projects. More recently, both AFGL and the Federal Aviation Administration (FAA) have become interested in using FSMs as operational visibility sensors. In the winter of 1984, the FAA tasked the Transportation Systems Center (TSC) to conduct an evaluation of all available visibility sensors. Thi evaluation was carried out at the AFGL Weather Test Facility (WTF) at the Otis Air National Guard Base. The work reported here is a continuation of the FAA tests, using the same evaluation methodology, for three FSM models made by different manufacturers.

The data analysis of this report was carried out by D. Schwartz (a coauthor) who is employed by the Systems Development Corporation. The authors would like to acknowledge the coworkers whose support made this study possible. Andy Caporale was responsible for day-to-day liaison with the test site. The WTF was manned by Leo Jacobs, Ralph Hoar and Clyde Lawrence. Fred Brousaides was the AFGL technical monitor.

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LIST OF ACRONYMS

AFGL	Air Force Geophysical Laboratory
ANGB	Air National Guard Base
AOS	Automated Observing System
AWOS	Automated Weather Observing System
AWS	Air Weather Service
DAS	data acquisition system
DOT	(U.S.) Department of Transportation
FAA	(U.S.) Federal Aviation Administration
FRSD	fractional residual standard deviation (RSD/Sensor 1)
FSM	forward scatter meter
GMT	Greenwich Mean Time (or Z-time) - Add 5 hours to Eastern Standard Time for Otis ANGB
IRED	infrared emitting diode
MAWS	Modular Automatic Weather System
MTBF	mean time between failures
RI	reporting increments
RMS	root mean square
RSD	residual standard deviation
RVR	Runway Visual Range
TSC	Transportation Systems Center
WTF	Weather Test Facility (at Otis ANGB)
Z-time	see GMT

1. INTRODUCTION

The United States Air Force Geophysical Laboratory (AFGL) is responsible for developing new weather instruments for the Air Weather Service (AWS). This report describes the evaluation of candidate visibility sensors for deployment in the Automated Observing System (AOS) being developed by AFGL for the AWS. The United States Department of Transportation (DOT) Federal Aviation Administration (FAA) has similar responsibilities to develop visibility sensors for civil aviation. In order to make the best use of government resources, the DOT Transportation Systems Center (TSC) and AFGL have worked together for many years to evaluate visibility sensors. Most of the joint studies have used the AFGL test site at Otis Air National Guard Base (ANGB) on Cape Cod. TSC's contributions to this joint effort have been to supply some of the test sensors and to develop an extensive library of data analysis software.

The primary goal of the visibility sensor evaluations has been to develop a forward scatter meter (FSM) that can be used to replace the transmissometer now used to measure visibility at airports. The first FSM was developed by AFGL in the early 1970s (Reference 1). The FSM offers a number of significant practical advantages over the transmissometer:

(1) It can be mounted on a simple post.

(2) It has a large range of response with consistent accuracy.

(3) It is relatively insensitive to window contamination.

(4) It is insensitive to background light.

(5) Relative calibration is possible at any time.

Possible disadvantages of the FSM are:

(1) It has different responses to different obstructions to vision.

(2) It uses a small averaging volume.

(3) Absolute calibration requires a transmissometer.

FSM evaluations have sought to quantify these possible disadvantages and to find a sensor that is stable, reliable and accurate.

This report evaluates forward scatter meters manufactured by three companies: EG&G Inc., HSS Inc. and Wright & Wright Inc. The evaluation period covered 17 months (December 1983 through April 1985). During the first 6 months of this period TSC evaluated a number of other visibility sensors (Reference 2) for the FAA. The methodology developed for that evaluation will be adopted for the present analysis. Because the FAA operates two different visibility systems, the analysis was designed to consider sensor performance for both systems. Since the FAA terminology will be used in this report, the FAA systems will be briefly defined. The FAA Automated Weather Observing System (AWOS) measures visibility from 1/4 to 5 miles. The FAA Runway Visual Range (RVR) System measures RVR between 150 and 6000 feet.

Visibility is a function of three variables:

(1) The observer

(2) The atmosphere

(3) The object being viewed

A visibility sensor does not measure visibility directly; it measures only the extinction coefficient, which is used to characterize the atmosphere. Standard equations, based on visibility research, are then used to estimate the visibility for a standard observer and a specified object. The two types of visibility sensor, transmissometers and scatter meters, obtain the extinction coefficient by different methods, as will be described in the following sections.

1.1 Transmissometer

The transmissometer consists of a projector producing a light beam which is measured at a distance b (the baseline) by a detector. When the atmosphere is clear, the detector is set to read 100 percent transmission (or near 100 percent to account for slight losses from atmospheric scattering). When the visibility is reduced, light will be scattered from the beam and the measured transmission will be less than 100 percent. The relationship between transmission T and extinction coefficient (sigma) is given by the equation:

$$T = \exp(-\sigma b). \qquad (1)$$

The transmissometer gives good readings when a sizable fraction of the beam is scattered out, but is susceptible to error when only a small portion of the beam is scattered. In the latter case, the scattering loss can be obscured by window losses, lamp drift or background light. The transmissometer becomes saturated when most of the light is scattered out of the

beam (T less than 1 percent). Thus, the total range of extinction coefficients which can be accurately measured by a single transmissometer is only a factor of ten. Frequent window cleaning is needed to maintain transmissometer accuracy.

In the transmissometer, the light beam and detector field of view must both be well collimated so that light scattered out of the beam is not detected. Thus, the transmissometer requires rigid towers and foundations to maintain alignment of the narrow beams.

Perhaps the primary feature of the transmissometer which allowed it to be readily accepted is that it is self-calibrating, as described above. Unfortunately, this feature also represents a practical problem; recalibration is impossible if a transmissometer fails during a period of reduced visibility.

1.2 Scatter Meter

A scatter meter operates on the opposite principle from the transmissometer. Instead of measuring the light remaining in a beam, the scatter meter measures the light scattered out of the beam. If a scatter meter detected all the scattered light, it would give the same information as the transmissometer, as long as the particles in the atmosphere do not absorb light (which is normally the case). Since a practical scatter meter cannot collect all the scattered light, a compromise is adopted where light scattered only in the forward direction (perhaps 20 to 40 degrees scattering angle) is collected. Such an instrument is termed a forward scatter meter. This range of scattering angles provides a signal for fog that is reasonably proportional to the total extinction coefficient even when the fog droplet size varies. Some variations are noted, however, for other obstructions to vision.

The forward scatter meter is not self-calibrating. Its output must be compared to that of a transmissometer to obtain an absolute calibration. In practice, the calibration is obtained by comparing the slope of the response for the two sensors for a number of fog events and adopting a mean calibration factor which relates FSM output to extinction coefficient. Once one unit of a particular FSM design has been calibrated against a transmissometer, a transfer calibration can be defined for other similar units. An artificial scatterer or "calibrator" is placed in the scattering region and the sensor output voltage noted. (Since a solid object will scatter much more strongly than fog, the calibrator must also attenuate the scattered signal in order to avoid saturating the sensor detector.) Another sensor can be calibrated by installing the calibrator and adjusting the gain to give the same output voltage. In order for this method to be practical, the calibrated scatterer must be (1) uniform spatially so that it represents the scattering obtained from fog and (2) stable in time so that the calibration voltage does not drift.

A satisfactory calibrator is required before forward scatter meters can be maintained in the field. Since such a calibrator can be used on a work bench even more easily than in the field, it is possible to keep a spare calibrated FSM which can be deployed whenever a field unit fails.

2. TEST CONFIGURATION

2.1 Sensor Descriptions

The Tasker RVR-500 transmissometer is currently deployed at airports on a 250-foot baseline to measure Runway Visual Range (RVR) values between approximately 600 and 6000 feet. The system consists of a projector, a receiver and a computer. The beam of light from the projector is intercepted by the receiver, the light pulses counted in the computer and converted to a visibility value. The presence of fog or other material which reduces the visibility along the path of the beam diminishes the detected light intensity proportionately, while any light from sources external to the beam which is scattered into the receiver will increase the apparent RVR. Transmissometers generally are expensive, difficult to maintain in a properly aligned condition, and limited in response below 600 feet RVR, which corresponds to Category IIIb landing conditions.

In these investigations, a series of four Tasker RVR-500 transmissometers with baselines of approximately 1000, 500, 300 and 40 feet are used as standards for comparison of the FSM responses. Details of the FSMs tested are given in the following sections.

2.1.1 HSS Inc. VR-301 Forward Scatter Meter

The HSS forward scatter meter consists of horizontal transmitter and receiver beams intersecting at a scattering angle of about 30 degrees. The light source is a light-emitting diode modulated at 3000 Hertz. The sample volume is defined by the intersection of the transmitted beam of light and the ray-cone which defines the field of view of the receiver system, as shown in Figure 2-1 below. The scattering volume is very small, approximately 400 cubic centimeters. Specifications of the VR-301 are given in Table 2-1.

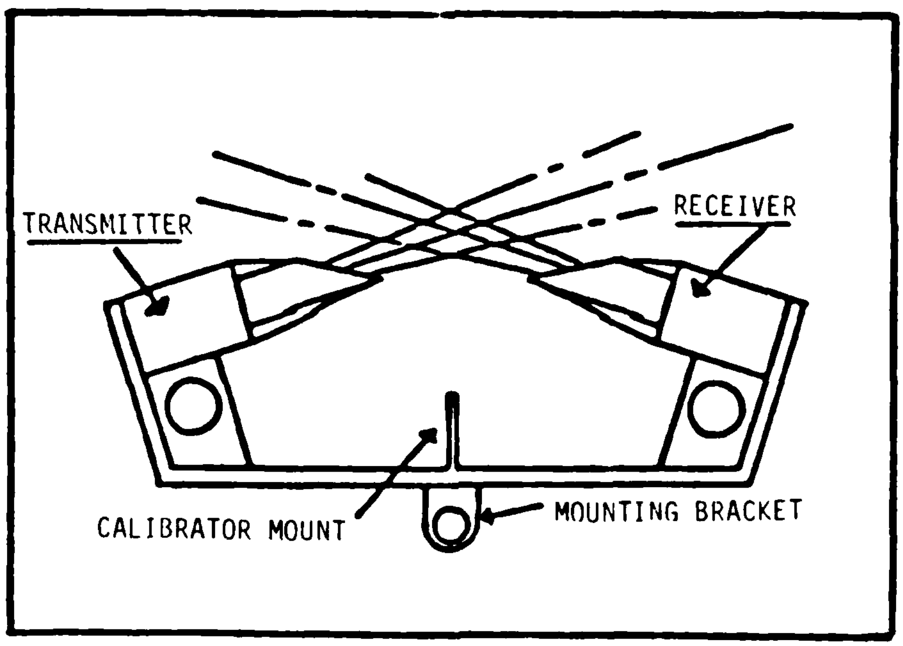

FIGURE 2-1. OPTICAL SCHEMATIC OF THE VR-301 VISIBILITY METER

TABLE 2-1. SPECIFICATIONS OF THE VR-301 FSM

PERFORMANCE CHARACTERISTICS

The performance characteristics stated below are based on a time constant of 30 seconds for the electronic circuitry of the VR-301 and the ability of the readout or recording system to cover the full output signal range (0 to 10 volts) of the VR-301 with appropriate resolution.

Visual Range Coverage (Note 1)	
X .1 Gain Setting	3 m to 30 km
X 1 Gain Setting	30 m to 300 km
RMS Noise Voltage (At Output)	
Night time	<1 millivolt
Day time	<2 millivolts
Linear Dynamic Range	10^4 to 1
Stability of Zero Setting	
Ambient Temperature Effects	≤2 millivolts
Long Term Drift	≤2 millivolts
Measurement Error (Std. dev.)	≤± 5%
(Includes All Calibration and Instrumental Errors)	
Maintenance	
MTBF	5.9 years
Calibration Check	Every 3 months
Clean Windows	Every 3 months

INSTRUMENT CHARACTERISTICS

Analog Output, proportional to the scattering coefficient	0 to 10 Volts
Scattering Angle Coverage	27° to 42°
Sample Volume	400 cm^3
Measurement Time Constant	30 sec

TABLE 2-1. SPECIFICATIONS OF THE VR-301 FSM (Cont.)

Spectral Features:	
Central Wavelength	0.89 μm
Bandwidth	0.08 μm
Source Characteristics	
Type	IRED
Lifetime	10 years
Modulation Frequency	3000 Hz
Detector	Hybrid Si-Sensor/Amplifier
Physical Characteristics (VR-301)	
Weight	14 pounds
Length	36 inches
Physical Characteristics (Auxiliary Control Unit)	
Weight	20 lbs
Size	16" L x 12" W x 6" H
Power Requirements	
Basic Instrument	4 W
No-Dew Windows	6 W
De-Icer Heaters	100 W
Environmental	
Temperature	-50° to +50° C
Altitude	0 to 10,000 ft
Weather	All Weather
Humidity	5% to 100%

Notes:
[1]Visual range coverage can be optimizd for specific applications by an internal potentiometer adjustment.

2.1.2 Wright & Wright Inc. FOG-15X Visual Range Meter

The FOG-15X visual range meter is a compact instrument designed for ease of installation, operation and maintenance. It measures the atmospheric forward scattering coefficient, which can be directly correlated to visual ranges from 100 feet to 9 miles. The FOG-15X consists of a light source and a photodetector separated by approximately four feet. The light source, a quartz halogen lamp radiating in the 0.4 to 1.1 micrometer wavelength range, is designed to project a cone-shaped beam of light over the angle of 8 to 20 degrees from the center axis toward the photodetector. The silicon photodetector looks toward the light source and is similarly configured to accept light only from a cone-shaped volume of the same dimensions. The resulting scatter volume is torus-shaped, with a total volume of 0.9 cubic feet (25,500 cubic centimeters).

Light energy scattered through a forward angle range of 16 to 40 degrees by particulates and aerosols in a sampling volume is measured by the photodetector. This measurement is linearly related to the atmospheric extinction coefficient, and can be correlated to visual range readings from 100 to 50,000 feet. Light source modulation of approximately 400 Hz and synchronous signal demodulation effectively eliminate interference from background luminance. Output signals are low impedance analog DC voltages of 0 to 10 volts which are transmitted by hard wire to the data acquisition system.

The light source for the basic instrument is a 15-watt halogen quartz lamp. An experimental model, the FG50 instrument, which employs a higher intensity lamp (5C watts) for improved signal to noise performance, was also tested. Further information on the FOG-15X system is given in Table 2-2 and in Figure 2-2 and 2-3.

TABLE 2-2. SPECIFICATIONS OF THE FOG-15X FSM

Dimensions of the FOG-15X Visual Range Meter are shown in drawing B-2237. Basic specifications of the FOG-15X are tabulated below:

Visual Range[1]: 100 feet to 9 miles

Accuracy: See Error Band Graph, drawing A-2168

Readout: Standard - 0 to +10 VDC analog voltage proportional to integrated scattering coefficient, where 10 volts corresponds to 10^{-3} cm^{-1}, or 100 feet visual range, and 0.01 volts corresponds to 10^{-6} cm^{-1}, or 100,000 feet visual range.

Integration Time Constant: 27 seconds

Operating Temperature Range: $-20^{o}C$ to $+50^{o}C$

Power: 105-125 VAC, 60 Hz, single phase, 300 watts

Size: 68.5" L x 21" H x 12" W (174 cm x 55 cm x 30.5 cm)

Weight: 54 lbs (24.5 kg)

Mounting: 1-1/2" schedule 40 pipe
(tapped to 11-1/2 threads/inch)

Electrical Connections: Terminal blocks in conduit body

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[1]Based on 5% liminal contrast ratio.

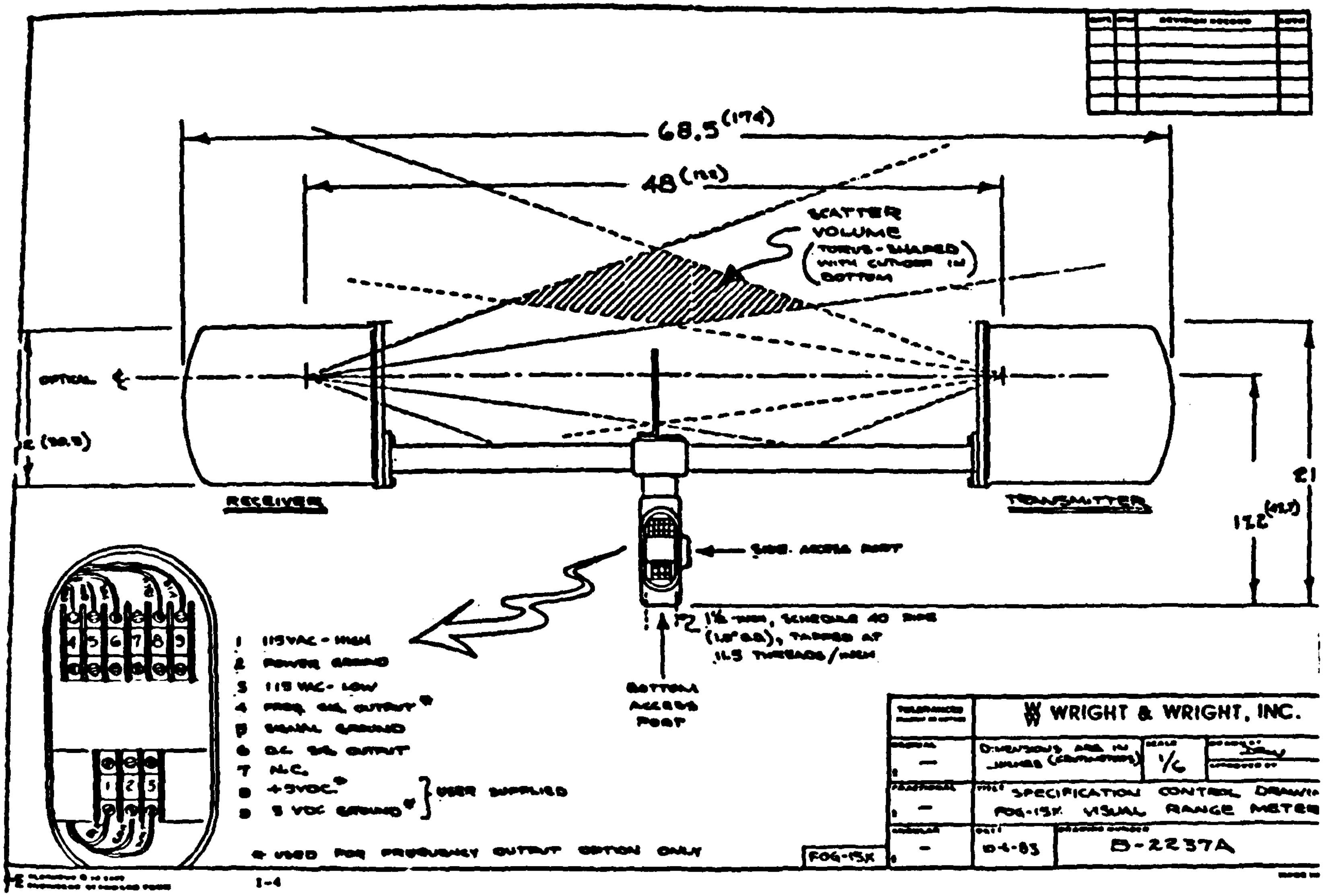


FIGURE 2-2. FOG-15X DETAILS

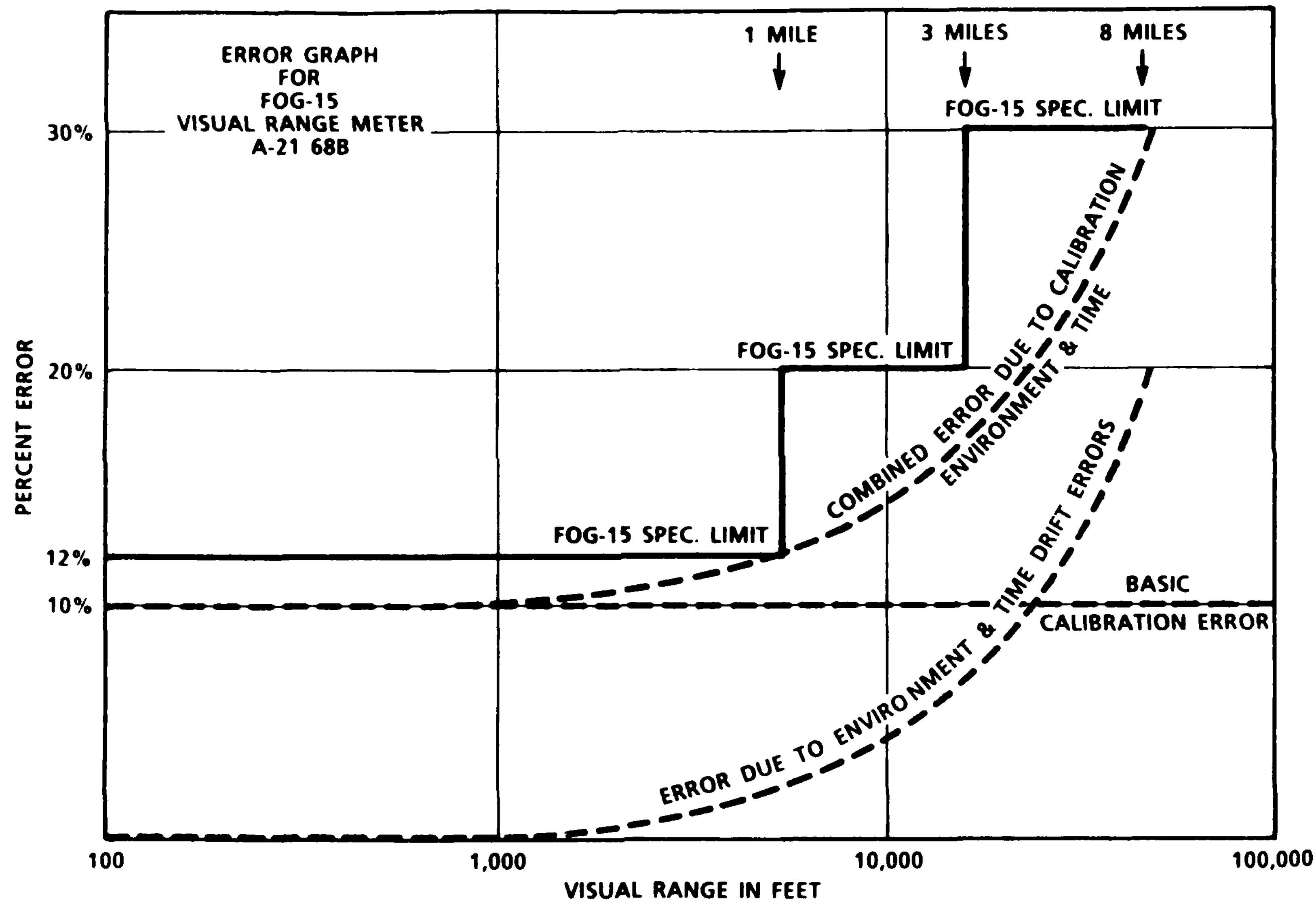


FIGURE 2-3. FOG-15X ERROR GRAPH

2.1.3 EG&G Inc. Model 207 Forward Scatter Meter

The EG&G Model 207 forward scatter meter was developed in the early 1970s under Air Force support and has been used extensively in a research mode for data collection. It has a large toroidal scatter volume (about 1.7 cubic feet or 48,000 cubic centimeters) and uses a mechanically chopped incandescent light source. Data from three of these FSMs are included in the data analysis. Specifications of the Model 207, which is no longer in production, are given in Table 2-3.

2.2 Test Standards and Site Layout

The reference standards used at the Otis test site are four transmissometers with baselines of 40 feet, 300 feet, 500 feet and 1000 feet. The 300-foot and 500-foot baselines are perpendicular to each other with the sensors being evaluated installed in a cluster grouped near the intersection of the two baselines. This four-baseline transmissometer array provided a visibility measurement range of 50 feet to 4 miles allowing evaluation of sensors for both AWOS and RVR ranges (see Section 1.). To maximize the availability of the transmissometer reference standards and to ensure validity of the data, an individual was employed at the site whose task was to check the transmissometers daily, clean the optics and recalibrate the units whenever atmospheric conditions (very high visibilities) allowed a calibration to be performed.

In addition to the test standards, there were nine forward scatter meters considered in the analysis, three by each of the three manufacturers. The HSS sensors designated as HSS1 and HSSA were set up for operation in the AWOS range, and the sensor designated as HSS2 covered the RVR range. The standard

TABLE 2-3. SPECIFICATIONS OF THE EG&G MODEL 207

Visual Range - Based on 5% Liminal Contrast Ratio:	200 feet to 20,000 feet.
Measurement Volume:	1.7 cubic feet minimum.
Measurement Accuracy:	±5% of forward scattered coefficient.
Power:	115 vac ±10%, 60 ±5% single phase, 200 watts.
Ambient Temperature:	-30°C to +50°C.
Weight:	135 pounds.
Mounting:	Single pipe with optional guy wires.
Deployment:	Unattended in ice, snow, rain and similar hostile environments.
Electrical Connections (Power and Signal)	Screw terminals behind access cover.
Orientation:	The instrument should be oriented so as to avoid direct sun rays into the receiver. The receiver optics should face in a northerly direction when used in the Northern hemisphere.
Time Constants (Linear Output)	
Operate and Test Positions:	20 sec nominal
All Other Test Positions	2 sec nominal

Note:
A step change will require several time constants for the output to reach the steady state.

Wright & Wright FOG-15X sensors were designated as the F15A and F15B. An experimental model with a higher intensity light source was designated as FG50. These sensors were intended to cover both AWOS and RVR ranges.

The EG&G instruments were designated the X-1, X-2 and Y sensors. These identical sensors also responded over both visibility ranges. These sensors were also used to provide a zero reference for the transmissometers during subsequent data reduction, as explained later.

The work reported here is a continuation of the sensor evaluation study previously reported (Reference 2) which contains the detailed test plan. For the previous analysis, sensor data was collected between 12/2/83 and 6/20/84. Subsequent data collection included the nine forward scatter meters listed above and the four transmissometers. The current analysis is based on data collected between 1/5/84 and 5/2/85.

2.3 Test Site Description

The sensor evaluation program was conducted at the USAF/Air Force Geophysical Laboratory (AFGL) test facility located at the Otis Air National Guard Base (ANGB) at Falmouth, Massachusetts, on Cape Cod. This site has the advantages of high incidence of fog and other adverse weather conditions, the availability of standard visibility measurement systems, the availability of a data acquisition and recording facility, and the presence of personnel experienced in conducting visibility sensor tests and in maintenance of the facility and of the visibility standards.

The layout of the visibility test site is shown in Figure 2-4. Note that all sensors except the Y sensor were grouped near

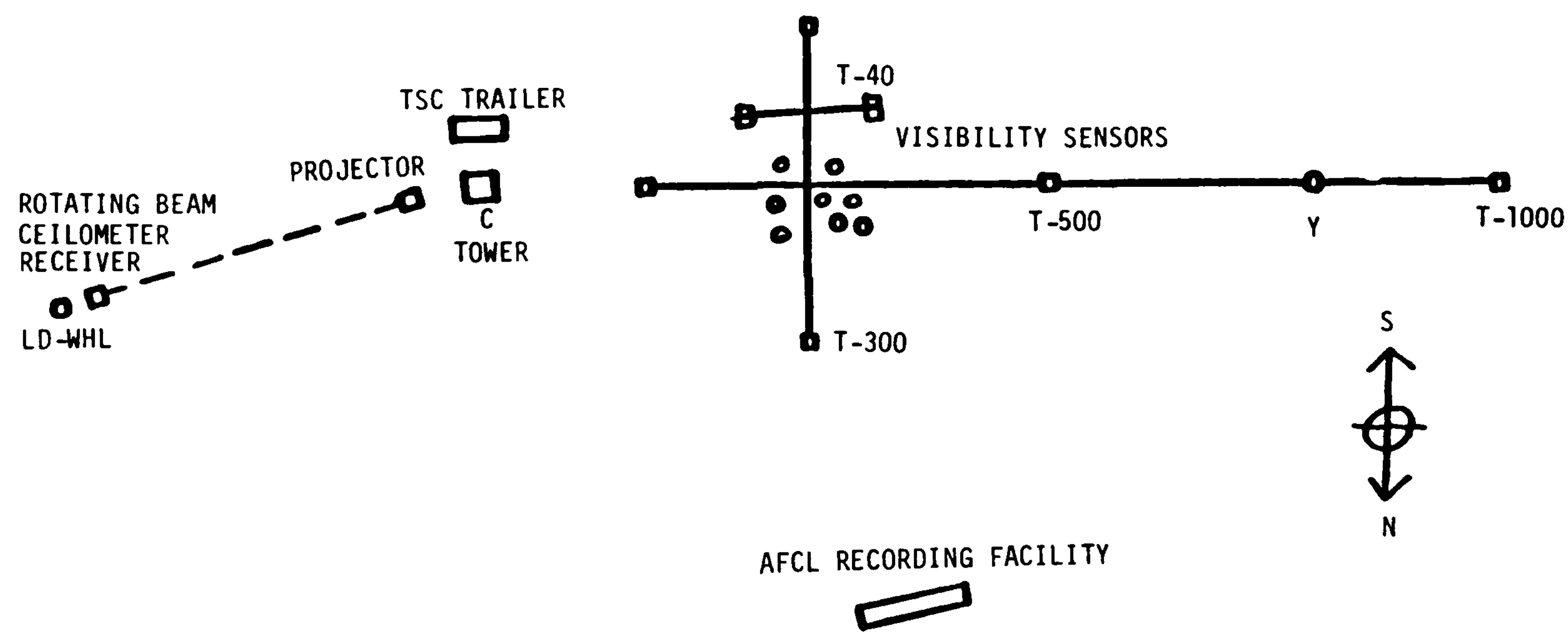


FIGURE 2-4. OTIS TEST SITE LAYOUT

the intersection of the 300-foot and 500-foot transmissometer paths. The Y sensor was located along the path of the 1000-foot baseline transmissometer so that it could be used in the 100-percent calibration adjustments for this standard.

2.4 Data Acquisition

The Otis data acquisition system (DAS) is the USAF Modular Automatic Weather System (MAWS), designed to acquire data from sensors generating an analog output voltage. This system samples voltage signals five times per minute and stores one-minute averages on industry compatible magnetic tapes. All sensors generated analog outputs except the reference transmissometers, which generate a pulse rate output and required a pulse to DC converter to interface to the DAS.

In addition to recording test and reference sensor data, the data collection included the hourly weather observations generated by the personnel of the Otis air traffic control tower, located about 1 mile from the test site, and the test site records maintained by USAF/AFGL site personnel pertaining to sensor calibration, sensor failures, repairs, or any observed anomalous sensor behavior.

To further investigate the weather affecting the sensors during low visibility episodes, a former Air Force meteorologist was provided as an on-site observer. During periods when on-site observations were available, these took precedence over weather readings from the control tower.

3. DATA PROCESSING

3.1 Analysis Procedures

Information from both the forward scatter meter sensors and the transmissometer standards was collected at the Otis ANGB between January 1984 and May 1985 and recorded on magnetic tape for analysis. Each week, the site weather observations and magnetic tapes containing a record for each minute of data were sent to TSC. Strip charts and performance files were generated from this raw data. Data was also gathered for the files necessary for further analysis with the SENSOR program (see Section 3.6). Prior to compilation of the final file of extinction coefficients (sigma), the data was normalized to calibrate, in effect, all of the instruments during a single event.

The sensor data was processed on a Digital Equipment Corporation (DEC) PDP-11/23 computer using the RT-11 operating system. The TSC computer program 062 was used to prepare a data file of extinction coefficients. Each extinction coefficient file ("performance file"), approximately 1.2 megabytes in length, contained seven days' worth of data, with an averaging time of one minute. Each record included the date, time, and a sigma value for each test and reference sensor at the Otis site. Only 13 sensors were used in this analysis, although data from as many as 58 sensors can be analyzed at the same time.

In addition to generating the performance files, the program produces a continous strip chart of the sensor sigma values arranged side-by-side, to be used for visual inspection of the data. A sample of the beginning of a typical strip chart is shown in Figure 3-1. Several features of the chart should be noted:

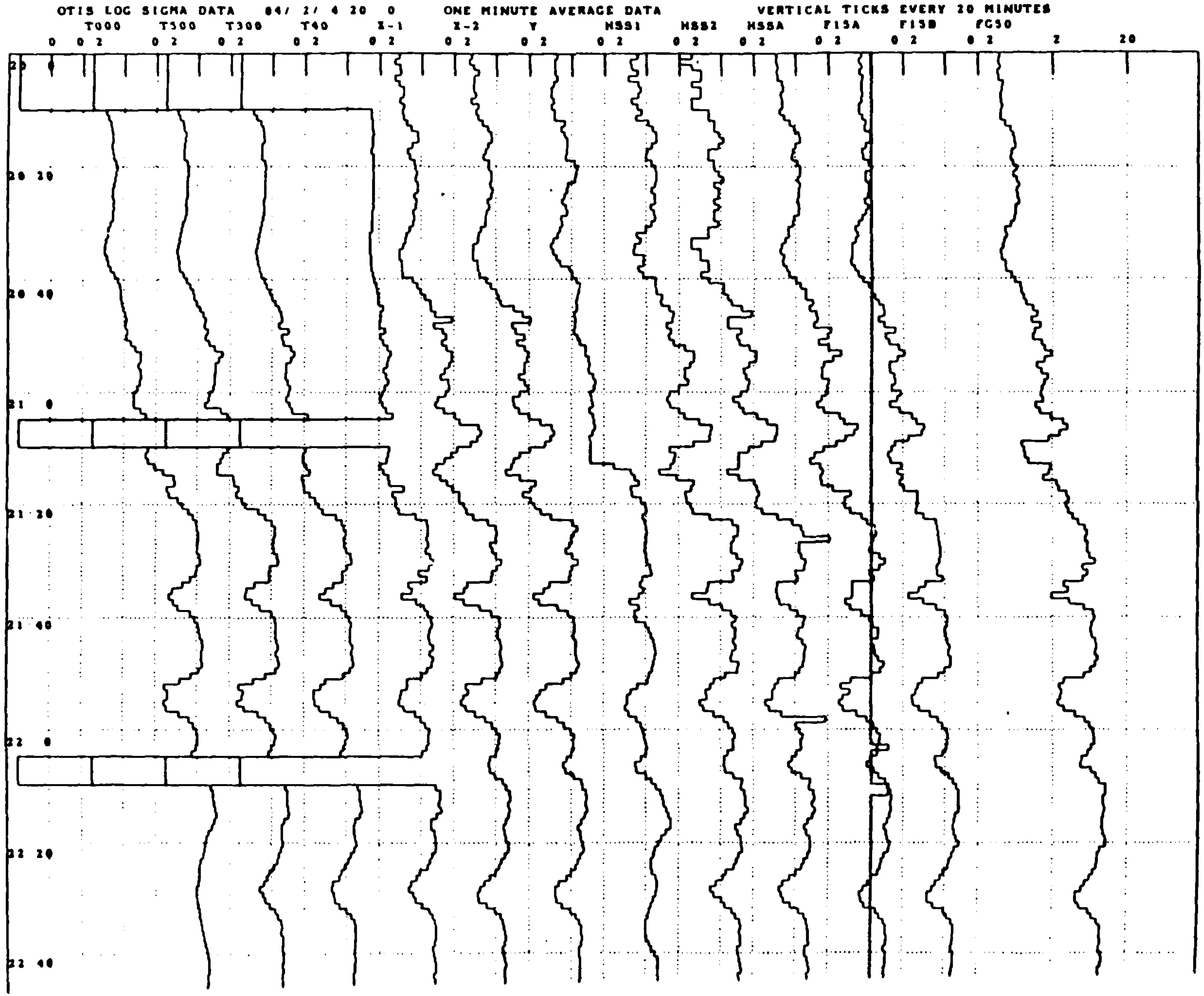


FIGURE 3-1. TYPICAL STRIP CHART

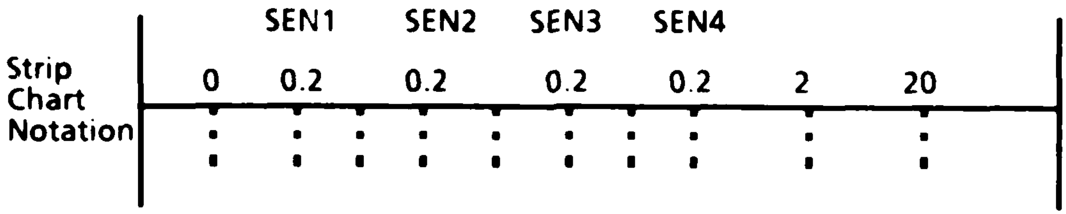
(1) The straight vertical line, which starts as the second line from the right, is an indication of failure of the sensor, F15B, since it does not respond to the increasing sigma values seen by the other sensors.

(2) Approximately once each hour, the transmitter for each transmissometer is turned off for about a minute, so that the receiver measures only the stray light which is scattered into it. The minimum value of the voltage measured corresponds to a background value, which is subtracted from all normal readings until the next background check. This is shown by the horizontal sections where the readings of all four transmissometers are greatly reduced. The length of time that the background value is displayed is increased by the computer program, so as to eliminate any transient effects due to turning the transmitter off and on.

(3) The degree of agreement of the FSMs and the transmissometers is seen from the degrees that the lines are equidistant, parallel to each other, and show the same series of changes in sigma value.

The scale on the strip chart is a complex superposition of linear and logarithmic scales for all 13 sensors. This is shown in Figure 3-2, which assumes for simplicity that there are only four sensors. Although a reading of sigma values from the strip charts cannot be made accurately, the charts provide a valuable tool to compare the response of the instruments to changing weather conditions on a temporal basis.

Assuming four sensors, the strip chart scale:



is a superposition of the following four individual scales:

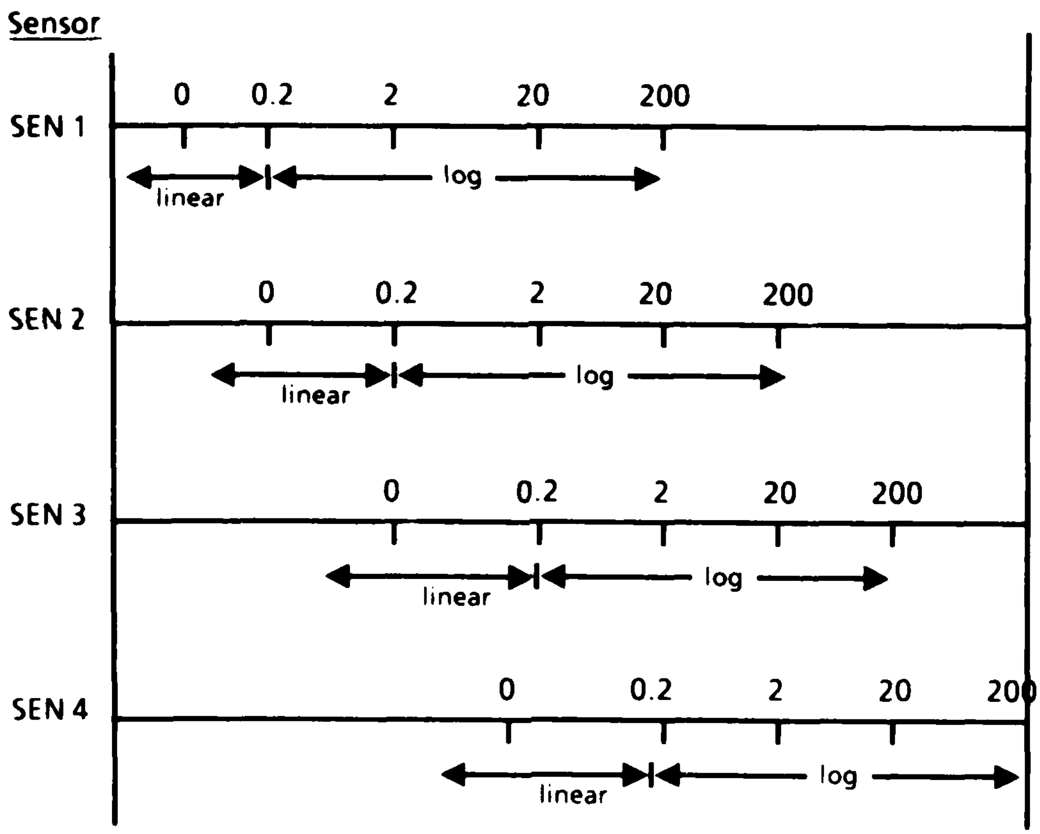


FIGURE 3-2. STRIP CHART NOTATION

The performance file is used as the data source for generating scatter plots with TSC computer program PHRX. These plots compare any designated pair of sensors over a selected time interval. For instance, to investigate the behavior of the instruments during a fog episode (which results in reduced visibility or increased sigma values), a scatter plot compares the responses of the instruments and plots a point on the curve for each one-minute interval. If the two sensors had completely identical responses, the points would all lie on a straight line at a 45° angle and pass through the point of origin. Adjustments to either or both slope and intercepts of the line can be made as an input to the program to show what the effect would be of changing the calibration or bias values of the instrument.

A typical scatter plot is shown in Figure 3-3. Note the following features from this plot:

(1) The two dashed lines represent variations of $\pm 15\%$ from the perfect 45° line.

(2) The fact that the bulk of the points lie in a line which has a slope of greater than 1.0 indicates that the HSSA sensor is somewhat more responsive to this reduced visibility event than the transmissometer.

(3) Regardless of what portion of the sigma range is displayed, the program performs a statistical analysis of all data with sigmas between 0.060 and 450, with the break points at 0.345, 0.760,1.27, 3.80 and 50.0. For each range in which there are data points, the program determines the best straight line through the points using a least-squares analysis, and presents this in terms of the slope of the line and the intercepts on both X and Y

DP3 OT0482 04 11401100004 AVERAGING INTERVAL= 1 MINS. HSTART=2100 HSTOP= 100

1ST SENSOR 32 HSSA 2ND: SENSOR 5 T500 YEAR: 1984 DAYS: 2/ 4- 2/ 5

K1= 1 000 D1= 0 00 K2= 1.000 D2= 0 00

DATA LIMITS	QUANTITY DATA POINTS	AVERAGE EXTINCTION COEFFICIENTS SENSOR 1	AVERAGE EXTINCTION COEFFICIENTS SENSOR 2	CORRELATION COEFFICIENT R	SLOPE K	Y-OFFSET D	X-OFFSET D	FIT R.S.D.	FRACTION SENSOR 1 R S.D.	VISIBILITY LIMITS (MILES)
040- 450	220	14.310	12.915	0.993	1.121	0.044	-0.040	0.945	0.0431	.004-30
.040-3 00	23	2 499	2.213	0.832	1.037	0.203	-0.197	0.367	0.2260	0 5-30
040-1.27	3	1 652	1.009	0.918	2.742	-1.116	0.407	0.120	0.0776	1.5-30
3 00- 50	197	15.922	14.164	0.991	1.120	0.057	-0.051	0.902	0.0417	.034-0.5
1 27-3 00	20	2.627	2.394	0.835	1.217	-0.280	0.236	0.370	0.2169	0.5-1.5
76-1 27	3	1.652	1.009	0.918	2.742	-1.116	0.407	0.120	0.0776	1 5-2.5

JPT= 2

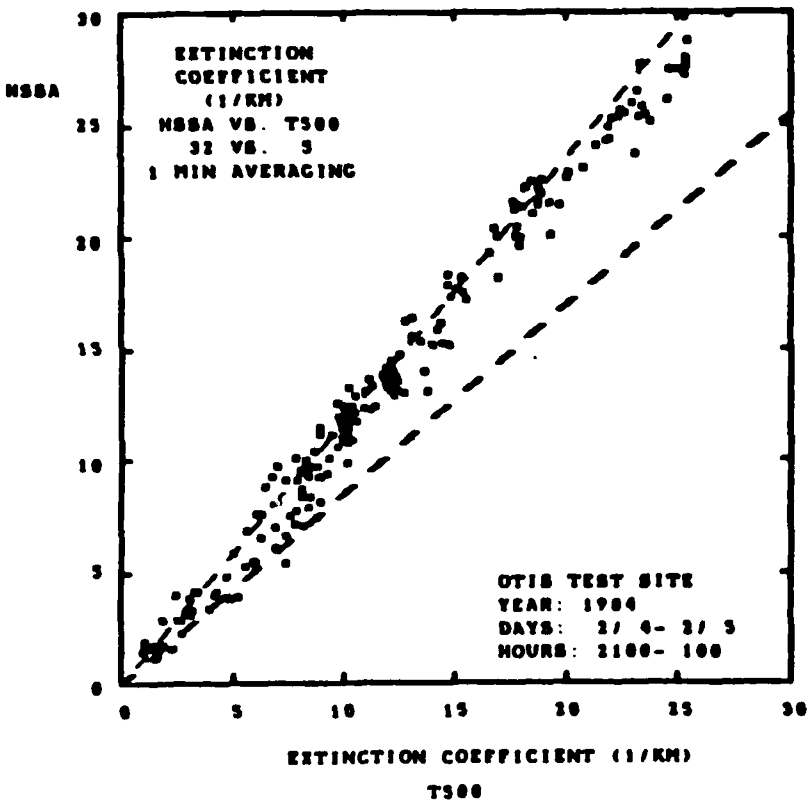


FIGURE 3-3. TYPICAL SCATTER PLOT

axes, with the average sigma values, and the correlation coefficient and residual standard deviation (RSD) of the line. The RSD is also expressed as a fraction of the test sensor sigma, which produces values relatively independent of the value of sigma.

(d) Good agreement in the representation of an incident of low visibility by two sensors is represented by high values of correlation coefficient, perhaps 0.99, and low values of fractional residual standard deviation (FRSD), on the order of 0.1 or below.

3.2 Normalization

Although all of the test sensors were calibrated prior to the initial test program at Otis ANGB, investigation of scatter plots from early incidents of poor visibility showed clearly that there was a discrepancy between the readings of the test sensors and those of the transmissometers. This discrepancy could have been due either to drift of the calibrations since the time of installation, or to inaccuracies in programming the conversions between sensor output voltage and extinction coefficients. To correct these discrepancies, data for the sensors was normalized, so that, for a given calibration event, they all showed the same response to fog as the 500-foot baseline transmissometer.

No corrections were made for the offset values. Since the test sensors, all forward scatter meters, tend to have more stable zero extinction coefficient values than the transmissometers, any shift in the zero values during the period of testing is normally associated with drifts in the transmissometer 100-percent calibration. Such transmissometer errors are corrected with the calibration file in program SENSOR, (see next section). All calibration constants were adjusted according to vendors' instructions prior to start of the test period. For further details on the normalization procedure, see Appendix A.

3.3 Calibration File

Calibration files are produced to provide a means for relatively continuous offset calibration adjustment for the transmissometers. This is done by comparing the transmissometer readings with measurements made by the EG&G forward scatter meters. A properly operating FSM will have very small offset errors. Previous investigations indicated that, for scatter plots of FSM against transmissometer, a slope of about 1.4 is observed under high visibility conditions. The intercept on the X-axis (FSM extinction coefficient = 0) is used as an offset value to correct for the calibration drifts of the transmissometers. For further details on the formation of the calibration file, see Appendix B.

3.4 Failure File

The failure file is intended to provide a record indicating when each of the sensors or transmissometers is not operating correctly. When the SENSOR program is run, data is bypassed during periods when any of the sensors involved in a study is in failure mode. Determination of the operational

status of the sensors is done by studying the strip charts. When necessary and available, additional information from the site logs may be used to assist in identifying the failure periods. For further details on the preparation of the failure file, see Appendix C.

3.5 Weather File

Weather files are determined from detailed lists of weather variations as compiled by the on-site weather observer at Otis ANGB. For periods during which these compilations are not available, the Federal Meteorological Forms 1-10 (Surface Weather Observations) from the Otis control tower have been used.

Table 3-1 lists the 14 categories of weather conditions which were considered in the sensor test analysis, with the codes corresponding to each category. Only one of these 14 conditions can occur at any time. When a change is made from one weather condition to another, a new entry is made in the weather file, which both terminates the old condition and starts the new condition.

Meteorologists use many other symbols to indicate categories of weather which are not considered separately in this analysis. For instance, a "-" following the letter code normally indicates light intensity, while "+" indicates heavy intensity. Both symbols are disregarded here. Other symbols and the assumptions which have been made in setting up the weather file are given in Table 3-2. Combinations not listed in either table are treated in a similar manner. For further details on the preparation of the weather file, see Appendix D.

TABLE 3-1. WEATHER CONDITIONS USED IN SENSOR ANALYSIS

Weather Condition	Letter Code	Numerical Code
Clear	C	01
Other	O	01
Haze	H	02
Fog	F	03
Drizzle	D or L	04
Rain	R	05
Snow	S	06
Ice Pellets	I or IP	07
Rain & Fog	RF	08
Rain & Ice	RI	09
Snow & Fog	SF	10
Rain & Snow	RS	11
Snow & Ice	SI	12
Snow Grains	SG	13
Drizzle & Fog	DF	14

TABLE 3-2. ADDITIONAL WEATHER CONDITIONS

Weather Condition	Letter Symbol	Treat As:
Rain Showers	RW	Rain
Snow Showers	SW	Snow
Blowing Snow	BS	Snow
Freezing Drizzle	ZD	Drizzle
Freezing Rain	ZR	Rain
Snow Pellets	SP	Snow
Thunderstorms	T	Rain
Fog & Haze	FH	Fog
Haze & Fog	HF	Haze
Snow & Haze	SH	Snow & Fog
Rain & Snow & Fog	RSF	Snow & Fog
Ice Pellets & Snow & Fog	ISF	Snow & Ice
Ice & Fog	IF	Ice Pellets
Rain & Ice & Fog	RIF	Rain & Ice
Rain & Snow & Ice & Fog	RSIF	Rain & Ice
Rain & Drizzle & Fog	RDF	Rain & Fog

3.6 SENSOR Analysis Program

The SENSOR analysis program was developed to evaluate sensor performance as measured during the field testing of the forward scatter meters. The primary input is the one-minute average extinction coefficient file (performance file) which is produced by running the O62 program on the weekly field test data. In addition, the calibration, failure and weather files discussed previously, are inputs to this program.

Four performance files, covering a 4-week test period, can be analyzed at one time. The analysis ignores periods when the failure file indicates that either the sensor or a necessary transmissometer standard is in failure mode. Analysis is also bypassed during periods when the transmissometers are in their background mode. The calibration file is used to provide corrections to the measured transmissometer sigmas to account for the drift of the instruments. The weather file is used to establish which of the 14 defined weather conditions exists during the period of the data record.

For analyses of both the RVR and AWOS range responses, data is included in the analysis only if the obstruction to visibility is considered uniform throughout the test region. The criterion for uniformity is that the sigma values for the 300-foot and 500-foot transmissometers, which are crossed halfway along their baselines, agree within 10%. For each sigma interval, a record is kept of the number of data points rejected by this criterion compared to those accepted. For AWOS evaluations, a further requirement is that independent 10-minute average extinction coefficients are used for the analysis. Only those 10-minute averages with a minimum of 5 valid one-minute sigma values are included in the evaluation.

To determine the acceptability of a FSM sensor for use over the AWOS range, the standard used for comparison is the 1000-foot baseline transmissometer. The visibility range for AWOS sensors is broken into 18 reporting increments (RI) as shown in Table 3-3, which shows the actual ranges of visibility and sigma values covered by each RI. The RI are defined by the daytime visibility equation. Accuracy statistics for AWOS sensors are given in terms of the number of RI differences between the sensor and the standard transmissometer. The SENSOR program produces output tables based on the RI.

For each four weeks of data, the AWOS Detail Tables consist of 120 tables for combinations of 8 sensors x 15 weather conditions (14 types plus All-Weather, the sum of all 14 types). Each table shows the number of data points (10-minute average sigmas) in each slot of an 18 x 18 matrix of the sensor RI values against the standard RI values. The AWOS Summary Tables, which are cumulative throughout the entire 60-week test period, consist of the same 120 tables. The RI values have been combined into four summary ranges (as shown in Table 3-3), and for each range, the number of data points with errors of $\leq$ 1RI, $>$ 1RI, $>$ 2RI, and $>$ 4RI, as well as the total number of samples, are shown in a 4 x 5 matrix. For samples of the SENSOR output tables, see Reference 2.

A similar arrangement is used for the RVR analysis done by the SENSOR program. The standard used for comparison here is the average of the two crossed transmissometer sigmas (300-foot and 500-foot baselines). However, for sigma values greater than 38 km^{-1}, the 500-foot transmissometer is out of its measurement range, and the standard is switched to the 40-foot baseline transmissometer. The one-minute average sigma values are broken down into seven ranges, as shown in Table 3-4, which also shows the equivalent day time visibility ranges. Accuracy statistics

TABLE 3-3. AWOS RANGE REPORTING INCREMENTS USED IN SENSOR PROGRAM

R.I. Number	Visibility Label	Visibility Range, Mi.	Sigma Km^{-1}	Summary Range Number
1	<.25	<0.187	>9.61	-
2	.25	0.187-0.375	9.61-4.81	1
3	.50	0.375-0.625	4.81-2.88	1
4	.75	0.625-0.875	2.88-2.06	1
5	1.00	0.875-1.125	2.06-1.60	1
6	1.25	1.125-1.375	1.60-1.31	2
7	1.50	1.375-1.625	1.31-1.11	2
8	1.75	1.625-1.875	1.11-0.96	2
9	2.00	1.875-2.25	0.96-0.80	2
10	2.50	2.25-2.75	0.80-0.66	2
11	3.00	2.75-3.25	0.66-0.55	3
12	3.50	3.25-3.75	0.55-0.48	3
13	4.00	3.75-4.50	0.48-0.40	3
14	5.00	4.50-5.50	0.40-0.33	3
15	6.00	5.50-6.50	0.33-0.28	4
16	7.00	6.50-7.50	0.28-0.24	4
17	8.00	7.50-9.00	0.24-0.20	4
18	>8.00	>9.00	<0.20	-

TABLE 3-4. RVR SIGMA RANGES USED IN SENSOR PROGRAM

Range Number	Sigma Ranges, Km-1	Visibility Ranges, Feet	Summary Range Number
1	1.5-2.5	6500-4000	1
2	2.5-4.0	4000-2500	1
3	4.0-7.0	2500-1400	2
4	7.0-11.0	1400-900	2
5	11.0-20.0	900-500	3
6	20.0-38.0	500-250	3
7	38.0-350.0	250-30	4*

*All-weather only

for RVR sensors are calculated in terms of values of the ratio of the sensor sigma to the standard sigma.

For each four weeks of data, the SENSOR program produces the RVR Detail Tables, a series of 120 tables for combinations of 8 sensor x 15 weather conditions (14 types plus all-weather). Each table shows the number of one-minute average data points in each of seven sigma ranges and nine ranges of the ratio of sensor/standard sigma. The ratio ranges are given in Table 3-5, which also shows the relationship to the RVR Summary error ranges. The RVR Summary Tables, which are cumulative throughout the entire 60-week test period, consist of the same 120 tables. The sigma ranges have been combined into four summary ranges, the last of which is only for the all-weather category, and for each range, the total number of samples, the number with $>$ 16.5% error, $>$ 25%, $>$ 35%, and $>$ 2X error, are shown in a 3 x 5 matrix. For samples of the SENSOR output tables, see Reference 2.

The complete analysis using the SENSOR program consists of 15 sets of output, each covering a 4-week data period. Further summarization and analysis of the data presented in the SENSOR outputs are included in Section 4 of this report.

3.7 Sensor Calibrations

One of the objectives of the original sensor evaluation tests was to insure that the FSM could be operated automatically and unattended with very infrequent maintenance required. In this regard, the sensors tested were to operate for 90 days after the start of the test period without any changes in calibration, maintenance, or cleaning of the optical systems. At this point, the manufacturers were allowed to recalibrate and perform maintenance on their instruments. The test then continued for

TABLE 3-5. RVR RATIOS OF SENSOR TO STANDARD USED IN SENSOR PROGRAM

Ratio Number	Ratio Label	Ratio Range	Summary Range Number*
1	0.000	0.000-0.500	1 2 3 4
2	0.500	0.500-0.750	1 2 3
3	0.750	0.750-0.800	1 2
4	0.800	0.800-0.835	1
5	0.835	0.835-1.165	
6	1.165	1.165-1.250	1
7	1.250	1.250-1.350	1 2
8	1.350	1.350-2.000	1 2 3
9	2.000	> 2.000	1 2 3 4

*Range 1 = >16.5%

Range 2 = >25% (actually +25% or -20%)

Range 3 = >35% (actually +35% or -25%)

Range 4 = > 2X

another 90 days with no further work on the instruments. During these two test periods, the stability of the FSMs was checked by periodically measuring the drift in the zero and calibrate voltages. When the 6-month period was completed, more frequent maintenance was performed. Calibration measurements were made both before and after each cleaning of the windows.

The calibration data has been plotted in Figures 3-4 for each of the nine sensors involved in this study. The two curves present the zero level and the scale factor (difference between calibrate and zero voltages) for each sensor. Data from two calibration filters is shown for the HSS1 and HSS2 sensors, with a horizontal offset between the two sets of data to increase readability. Only a single calibration filter was used with the other sensors. Scale factor variations are shown as percentage changes from the initial scale factor voltage. Vertical steps on the scatter plot correspond to window cleaning, with the lower value occurring prior to cleaning. These steps are most pronounced on the HSS sensors. The zero drift is also shown as the change from the initial value, expressed in terms of the extinction coefficient response of each sensor. The EG&G sensors were replaced whenever problems developed. For each of the three sensors, three instruments were used during the test period. New initial values of zero level and scale factor were established after each change.

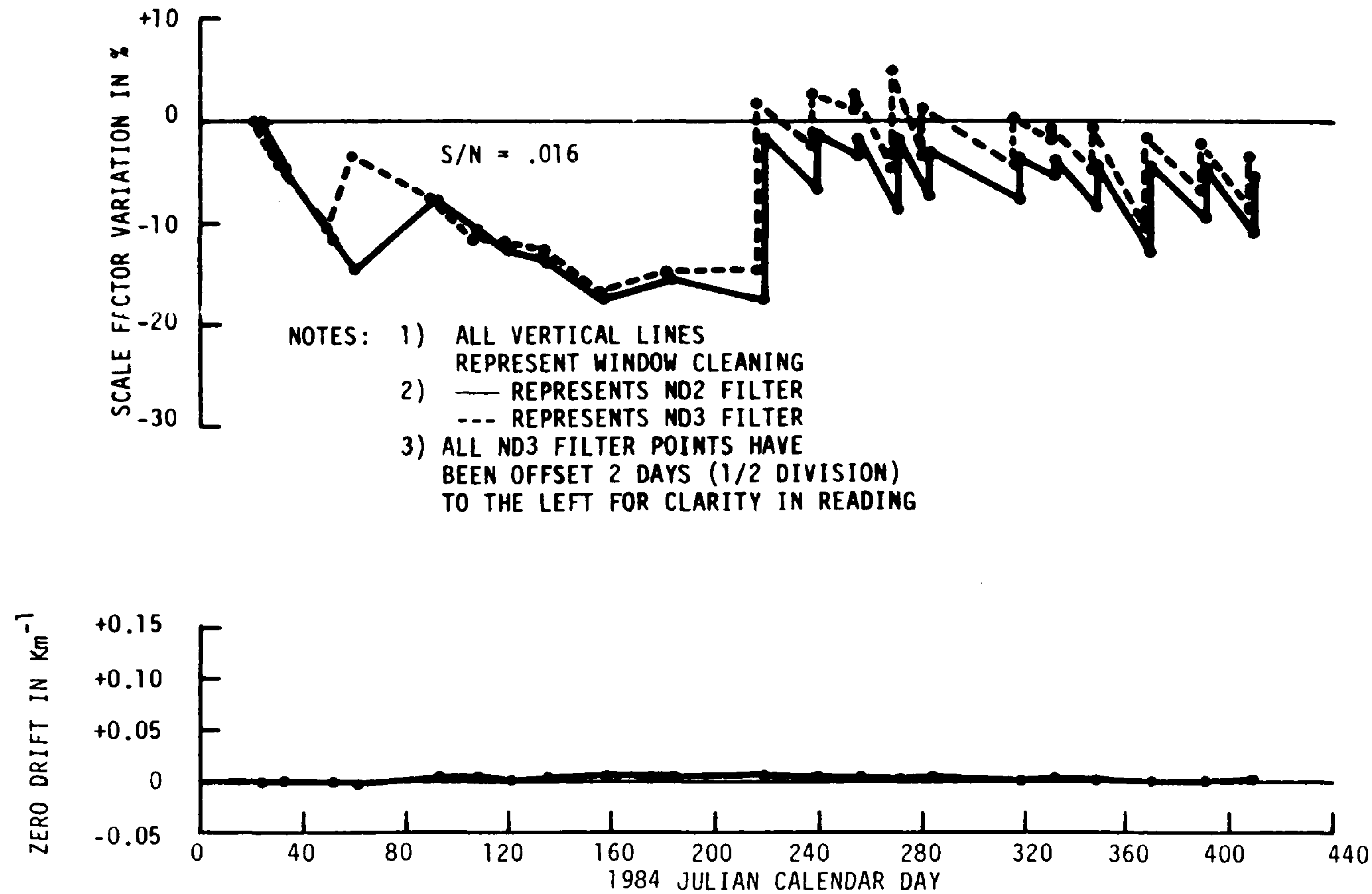


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (HSS1)

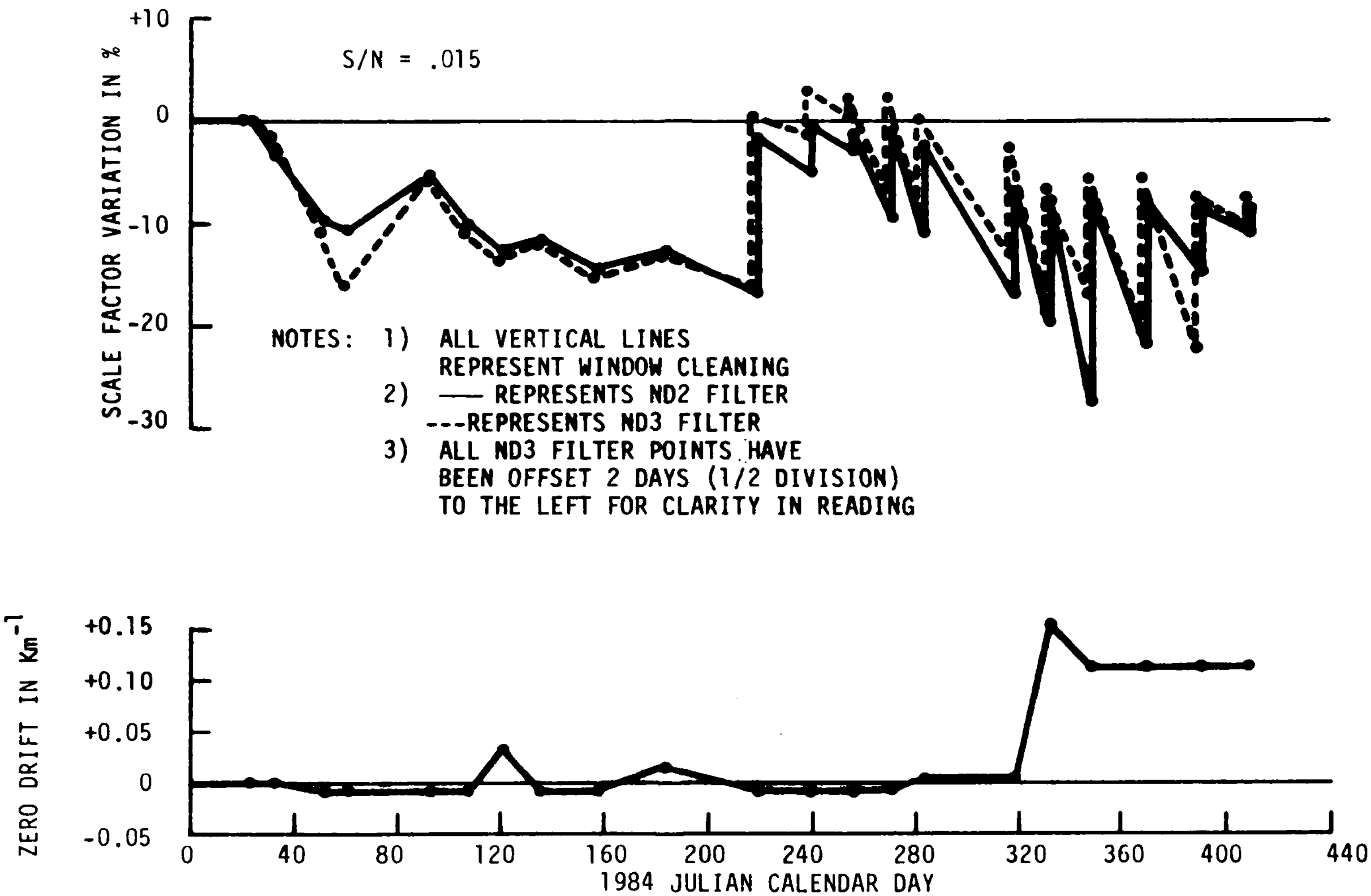


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (HSS2) (Cont.)

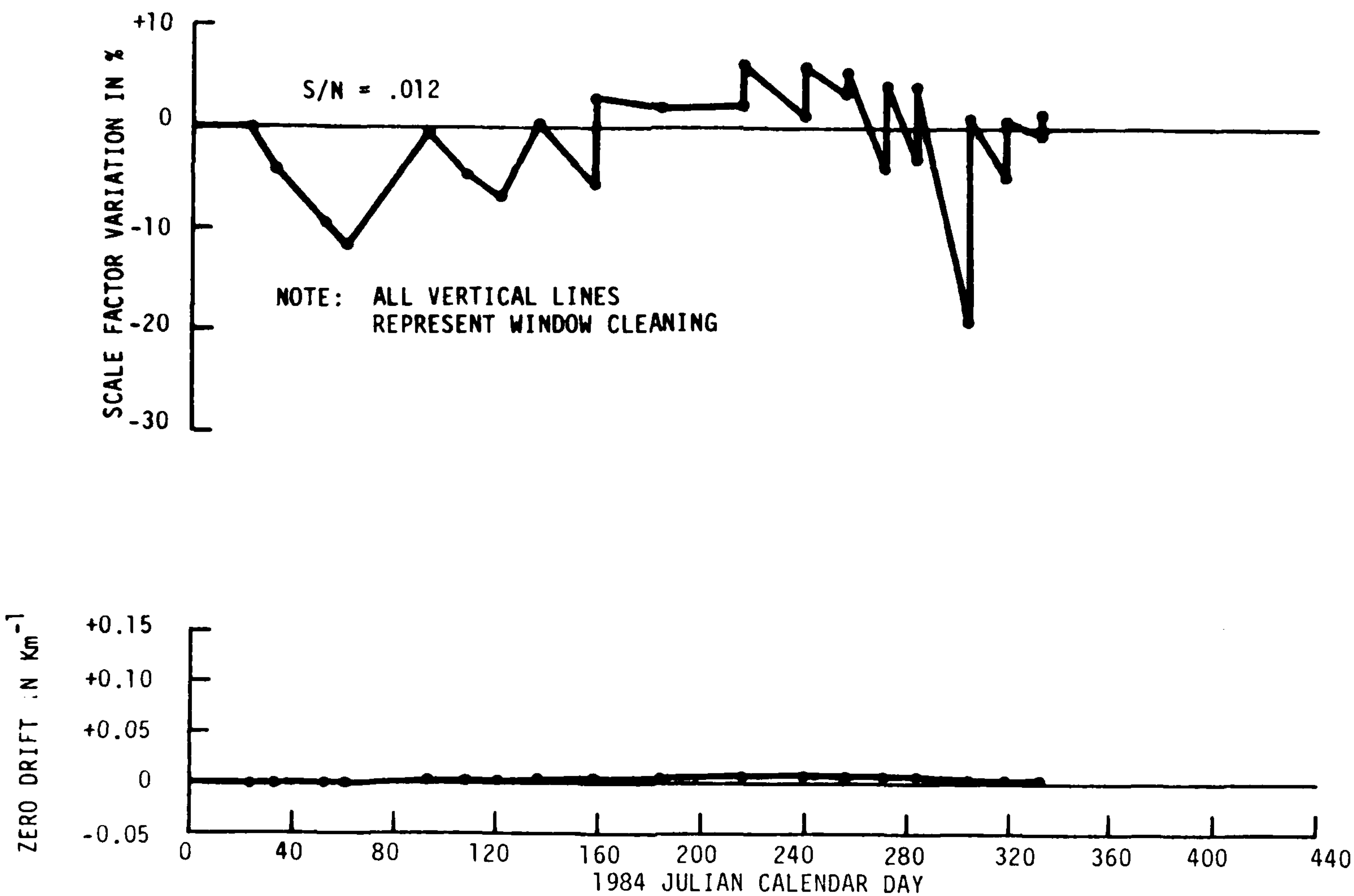


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (HSSA) (Cont.)

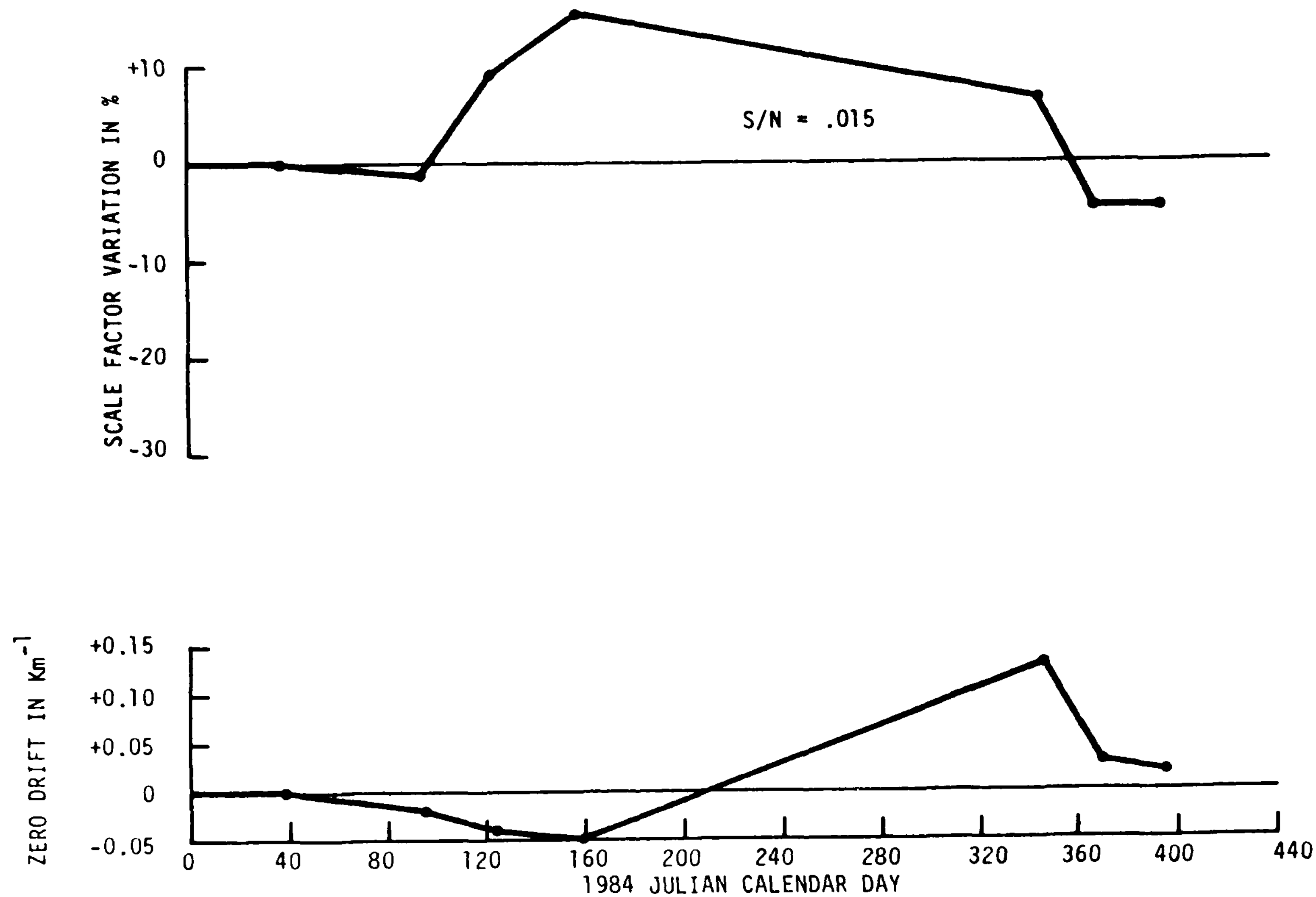


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (F15A) (Cont.)

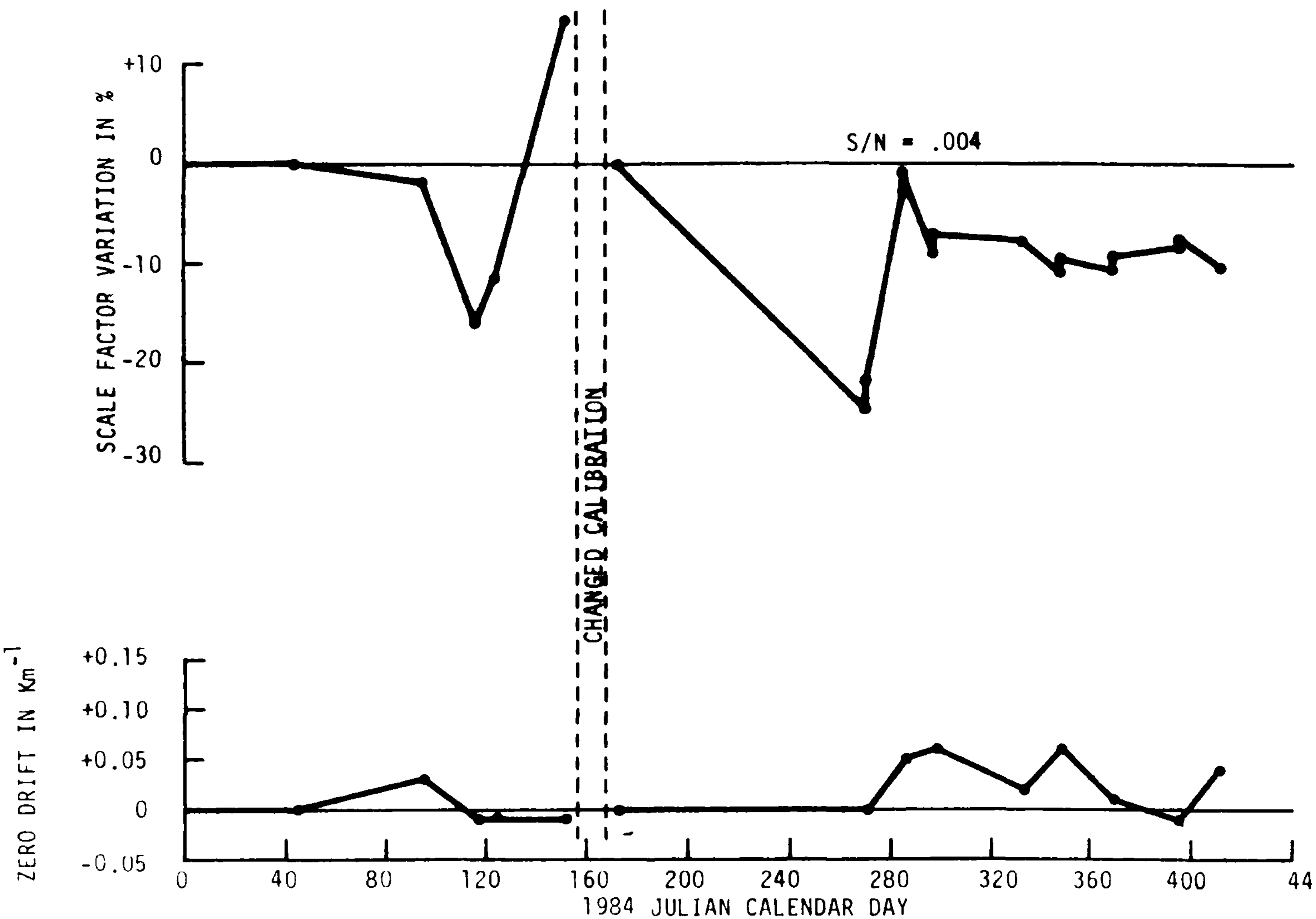


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (F15B) (Cont.)

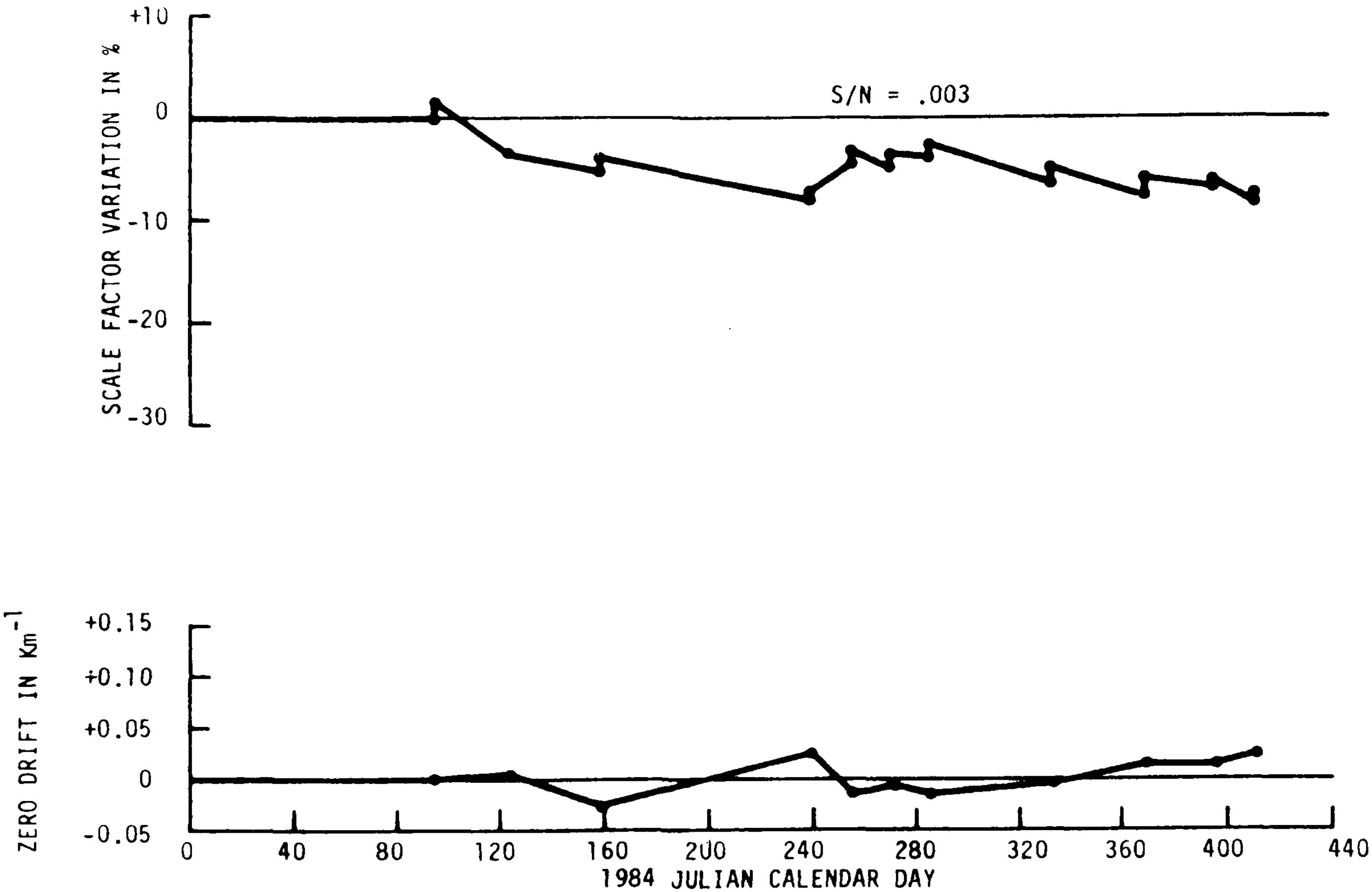


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (FG50) (Cont.)

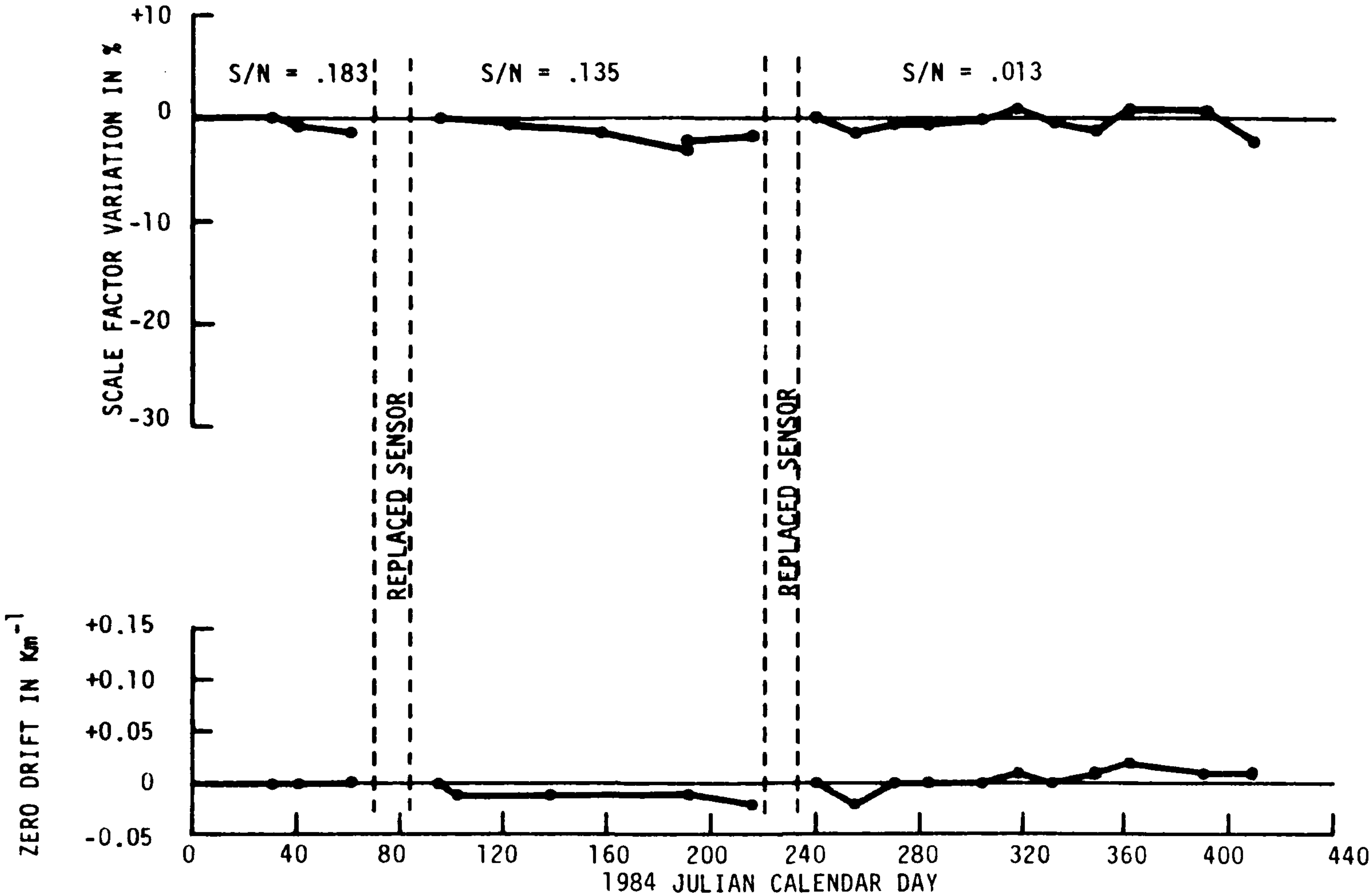


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (X-1) (Cont.)

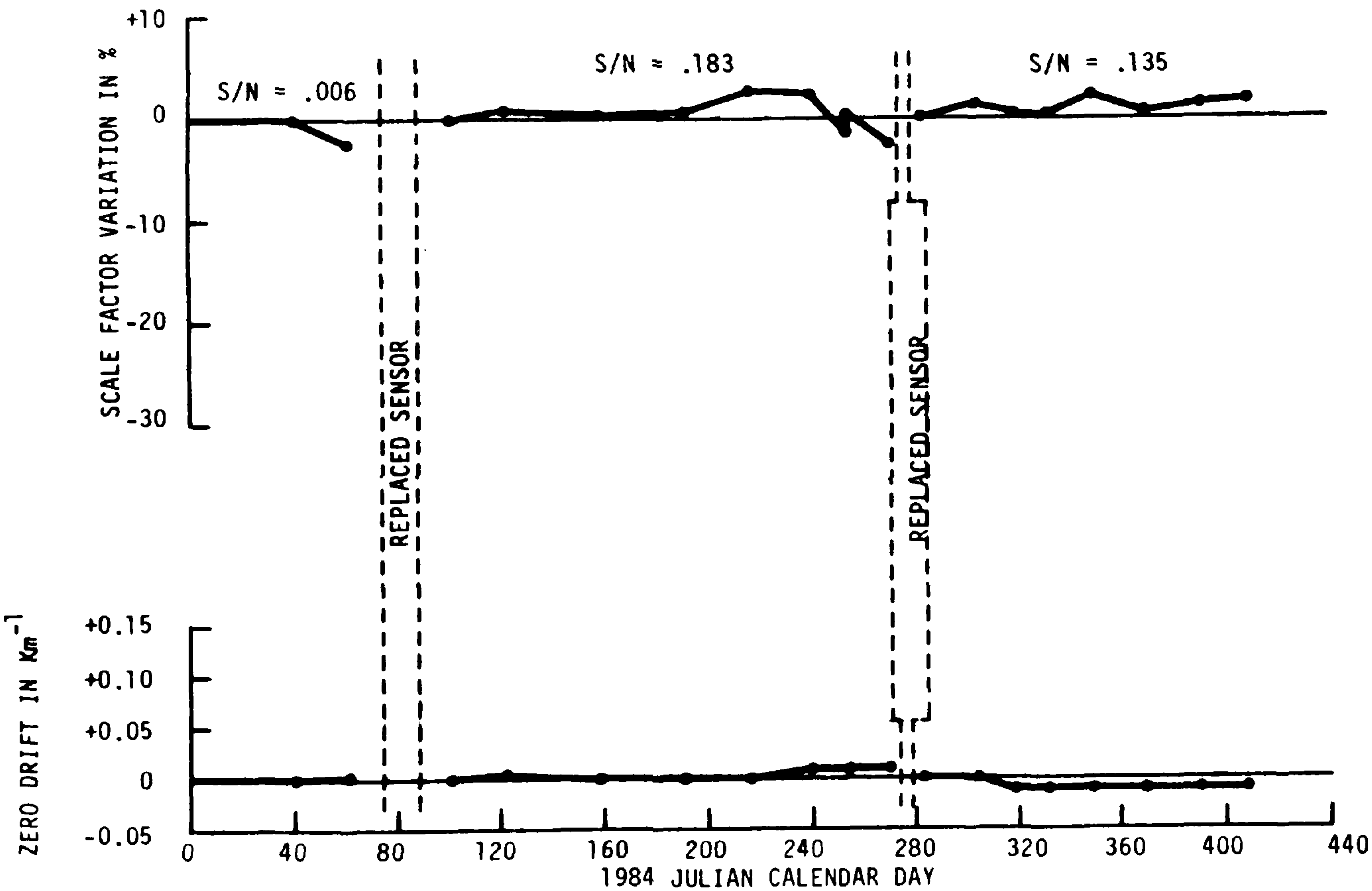


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (X-2) (Cont.)

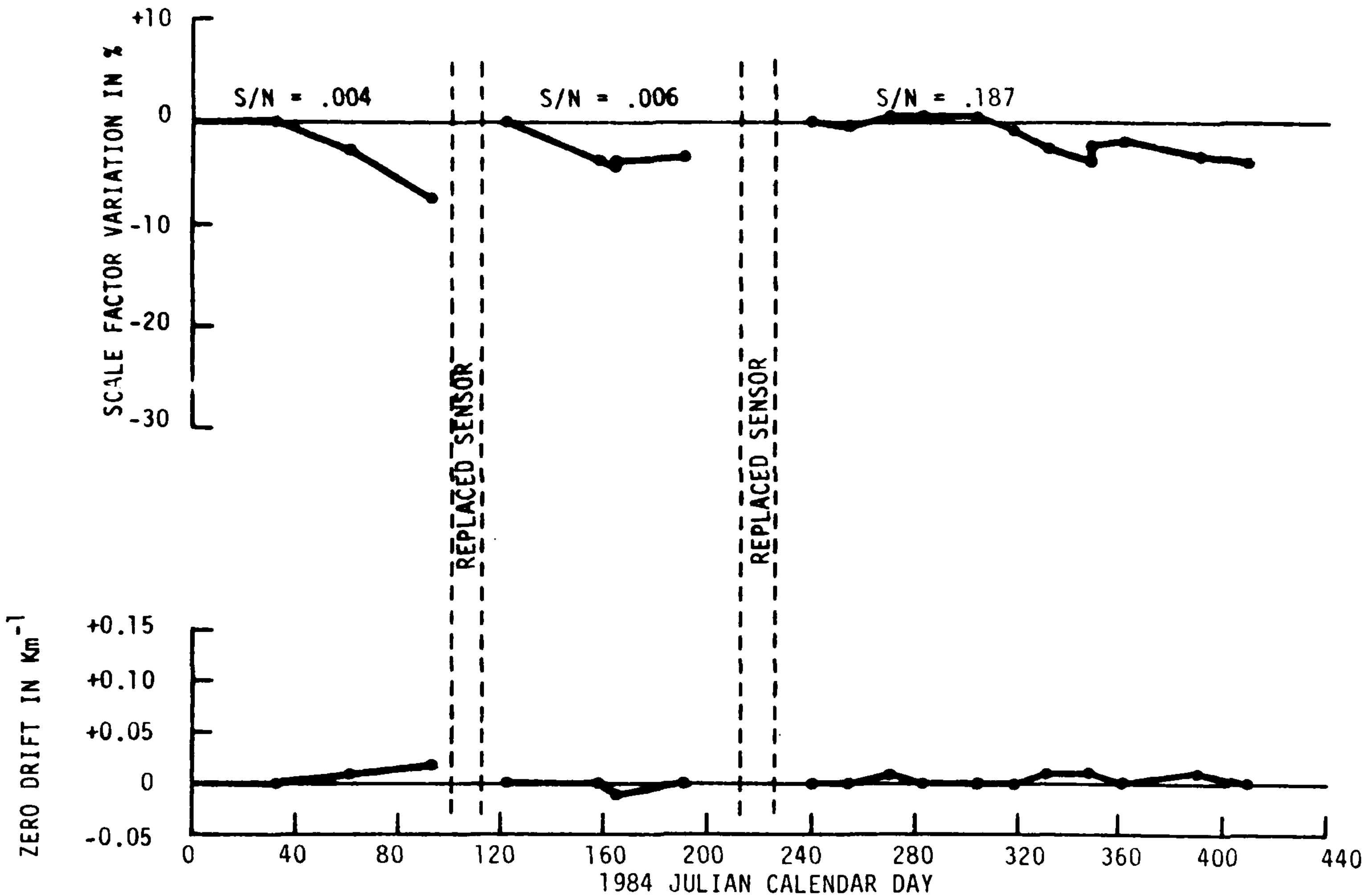


FIGURE 3-4. SENSOR CALIBRATION HISTORIES (Y) (Cont.)

4. RESULTS

The analysis of test data used two different approaches: 1) Detailed analysis of selected events and 2) Statistical analysis of all data. Weather information from Otis Air National Guard Base and the strip charts showing sensor response as a function of time were compared to choose a series of low visibility incidents which were investigated in detail (Sections 4.1 through 4.3). The statistical analysis, which considered all of the data rather than just a few incidents, first compared the responses of the 300-foot and 500-foot baseline transmissometers (Section 4.4) before comparing each sensor to the "standard" transmissometer (Sections 4.5 through 4.7).

4.1 Low Visibility Periods

4.1.1 Otis Weather Data

A review was made of all the available Surface Weather Observations (Form MF1-10) from the Otis Air National Guard Base to identify suitable low visibility periods for analysis. The minimum value of surface visibility recorded during each day is listed in Table 4-1. For minimum recorded visibilities of less than one mile, the times in GMT (subtract five hours to get Eastern Standard Time) during which visibilities were one mile or below are listed. If the minimum visibility was low enough for a sufficiently long period, the incident was considered for analysis.

4.1.2 Strip Chart Data

The strip charts were also searched to determine when low visibility was observed by the sensors. For acceptance as a genuine phenomenon, the incident had to be observed by the transmissometers as well as most of the FSM sensors. Very

TABLE 4-1. OTIS WEATHER DATA

Date	Min Vis mi	Times Visibility < 1 mi
1/5/84	3/4	1244-1344
1/6	0	0333-0555, 0852-1130, 1723-2400
1/7	1/4	0000-0239
1/8	10	
1/9	4	
1/10	1 1/2	
1/11	1/2	0734-0907
1/12	1/2	1747-1930
1/13	5	
1/14	1 1/2	
1/15	2	
1/16	7	
1/17	5	
1/18	1/2	2120-2330
1/19	1 1/8	
1/20	7	
1/21	10	
1/22	15	
1/23	8	
1/24	4	
1/25	1/8	0835-1405
1/26	7	
1/27	5	
1/28	3/8	0209-0317
1/29	6	
1/30	4	
1/31	5/8	1244-1620

Date	Min Vis mi	Times Visibility < 1 mi
2/1/84	15	
2/2	15	
2/3	7	
2/4	1/8	1308-1623, 2130-2400
2/5	0	0000-1655
2/6	2	
2/7	4	
2/8	15	
2/9	10	
2/10	15	
2/11	1 1/2	
2/12	1/8	0441-1250
2/13	0	0952-1624, 2236-2400
2/14	1/16	0000-1555, 2246-2400
2/15	1/16	0000-0311, 2315-2400
2/16	1/16	0000-0955, 1147-1240
2/17	3/4	1637-1855
2/18	1	
2/19	1 1/2	
2/20	3/4	1402-1418
2/21	12	
2/22	7	
2/23	NA	
2/24	1/4	1117-1609
2/25	1 1/2	
2/26	5	
2/27	15	
2/28	1/4	2213-2400

Date	Min Vis mi	Times Visibility < 1 mi
2/29/84	1	
3/1	15	
3/2	20	
3/3	20	
3/4	20	
3/5	2	
3/6	5/8	1219-1415
3/7	15	
3/8	15	
3/9	1/4	0745-2019
3/10	12	
3/11	1/4	1537-1712
3/12	10	
3/13	3/4	1438-1640
3/14	3/16	1149-1233, 1308-1450
3/15	20	
3/16	5/16	1205-1434, 2248-2336
3/17	1	
3/18	1 1/4	
3/19	1 1/2	
3/20	1	
3/21	1/4	0041-0118, 0511-1155, 2144-2400
3/22	1/4	0000-0243
3/23	7	
3/24	10	
3/25	12	
3/26	7	

Date	Min Vis mi	Times Visibility < 1 mi
3/27/84	15	
3/28	15	
3/29	2	
3/30	NA	
3/31	NA	
4/1	20	
4/2	12	
4/3	12	
4/4	12	
4/5	1	
4/6	3/4	0020-0035
4/7	7	
4/8	5	
4/9	10	
4/10	1	
4/11	2	
4/12	12	
4/13	15	
4/14	5	
4/15	1/4	2045-2255
4/16	1/4	0245-1213, 1651-2214
4/17	1/8	0051-0725, 1039-1223
4/18	1	
4/19	1/16	0037-0755
4/20	1 1/2	
4/21	2 3/4	
4/22	12	
4/23	10	

TABLE 4-1. OTIS WEATHER DATA (Cont.)

Date	Min Vis mi	Times Visibility < 1 mi
4/24/84	1/8	0940-1603
4/25	2	
4/26	4	
4/27	15	
4/28	15	
4/29	20	
4/30	10	
5/1	1/4	0748-0825
5/2	15	
5/3	3	
5/4	1/4	1015-1148
5/5	1/2	0037-0359
5/6	15	
5/7	1/16	0809-0950
5/8	3/16	1807-2110, 2123-2300
5/9	1/4	0227-0318, 0455-0649
5/10	10	
5/11	5	
5/12	1 3/4	
5/13	2 1/2	
5/14	[illegible]	
5/15	15	
5/16	10	
5/17	10	
5/18	15	
5/19	10	
5/20	3	
5/21	[illegible]	

Date	Min Vis mi	Times Visibility < 1 mi
5/22/84	5	
5/23	1/4	0351-1023
5/24	3	
5/25	12	
5/26	1/4	1239-1329, 2039-2125, 2217-2400
5/27	[illegible]	0000-0227, 0431-0549
5/28	1 1/2	
5/29	1/16	0817-1328
5/30	5	
5/31	3/4	1714-1722
6/1	3/4	2335-2348
6/2	3/4	2244-2249
6/3	1 1/2	
6/4	12	
6/5	4	
6/6	5	
6/7	2	
6/8	2	
6/9	2	
6/10	2 1/2	
6/11	2 1/2	
6/12	3	
6/13	2	
6/14	2	
6/15	[illegible]	
6/16	5	
6/17	2	

Date	Min Vis mi	Times Visibility < 1 mi
6/18/84	1 1/8	
6/19	1/4	0555-0655, 1609-1730
6/20	1/16	0009-0255
6/21	15	
6/22	15	
6/23	7	
6/24	7	
6/25	1/4	1202-1255, 1520-1533
6/26	1/8	0455-0545, 0647-0814, 0921-1233
6/27	1/16	0920-1023
6/28	5	
6/29	2	
6/30	0	0455-1125
7/1	0	0210-1148
7/2	1/16	0416-0910
7/3	1/4	0855-1050
7/4	2 3/4	
7/5	2	
7/6	5	
7/7	1	
7/8	1 1/4	
7/9	12	
7/10	10	
7/11	0	0915-1141
7/12	2 1/2	
7/13	10	
7/14	7	

Date	Min Vis mi	Times Visibility < 1 mi
7/15/84	2	
7/16	1/2	1355-1438, 2345-2400
7/17	1	
7/18	3/4	0940-1040, 1110-1232
7/19	4	
7/20	6	
7/21	1/2	1541-1555, 1824-1837
7/22	7	
7/23	1/4	0504-0555
7/24	5	
7/25	10	
7/26	15	
7/27	1 1/2	
7/28	1	
7/29	6	
7/30	10	
7/31	7	
8/1	2 3/4	
8/2	2 3/4	
8/3	1	
8/4	0	0255-1246
8/5	1/16	0414-1231
8/6	1 3/4	
8/7	0	0955-1138
8/8	0	0406-0431, 0610-1919
8/9	1/8	0122-0730, 0955-1536
8/10	1/4	0950-1306
8/11	1/8	0615-1041

TABLE 4-1. OTIS WEATHER DATA (Cont.)

Date	Min Vis mi	Times Visibility < 1 mi
8/12/84	1/8	0240-0555, 0855-1412, 2259-2400
8/13	1/4	0000-1120, 1255-1345, 1535-1629
8/14	0	0930-1133
8/15	0	0515-0949
8/16	1 3/4	
8/17	5	
8/18	12	
8/19	12	
8/20	15	
8/21	10	
8/22	12	

8/23 - 10/10/84 Not Available

Date	Min Vis mi	Times Visibility < 1 mi
10/11	4	
10/12	0	0032-0945
10/13	5	
10/14	3/4	1455-1510, 1655-1755
10/15	2	
10/16	6	
10/17	6	
10/18	5	
10/19	1/4	0341-0555, 1055-1224
10/20	0	0747-1444
10/21	0	2124-2400
10/22	1/16	0000-0718, 2155-2400
10/23	1/4	0000-0155, 1229-1321
10/24	2 1/2	

Date	Min Vis mi	Times Visibility < 1 mi
10/25/84	4	
10/26	1/4	2128-2400
10/27	1/16	0000-0212, 0616-1408
10/28	1/8	1555-2400
10/29	1/16	0000-0755, 1048-1528
10/30	3	
10/31	10	
11/1	10	
11/2	1/8	0406-0825
11/3	12	
11/4	10	
11/5	1/4	0830-1355
11/6	1/4	0040-0122
11/7	10	
11/8	12	
11/9	12	
11/10	10	
11/11	3/4	1821-1827
11/12	1 1/2	
11/13	12	
11/14	2	
11/15	15	
11/16	7	
11/17	12	
11/18	12	
11/19	10	
11/20	15	
11/21	15	

Date	Min Vis mi	Times Visibility < 1 mi
11/22/84	10	
11/23	12	
11/24	10	
11/25	10	
11/26	4	
11/27	3	
11/28	1/16	0605-1126
11/29	3/4	1255-1313
11/30	10	
12/1	6	
12/2	10	
12/3	2	
12/4	10	
12/5	15	
12/6	1/2	1355-1503
12/7	4	
12/8	15	
12/9	10	
12/10	1/2	2345-2400
12/11	0	0000-0540, 0838-1555, 2118-2400
12/12	1/4	0241-0738, 1127-1406
12/13	3	
12/14	3	
12/15	3/4	2044-2216
12/16	3/4	0827-0839
12/17	1	
12/18	1/8	0855-1244, 1336-1522

Date	Min Vis mi	Times Visibility < 1 mi
12/19/84	1	
12/20	2	
12/21	10	
12/22	1/8	2004-2224
12/23	7	
12/24	3	
12/25	4	
12/26	15	
12/27	2 1/4	
12/28	1/8	0655-1410-1640-2055
12/29	5	
12/30	8	
12/31/84	12	
1/1/85	1/4	1555-2400
1/2	1/8	0000-0210, 0337-0808, 1331-1643
1/3	5	
1/4	10	
1/5	1/4	1055-1441
1/6	10	
1/7	3	
1/8	1/2	0815-1213, 0738
1/9	15	
1/10	12	
1/11	10	
1/12	10	
1/13	15	
1/14	10	

TABLE 4-1. OTIS WEATHER DATA (Cont.)

Date	Min Vis mi	Times Visibility < 1 mi
1/15/85	5	
1/16	15	
1/17	5/8	1504-1727
1/18	2	
1/19	1/2	1701-1807
1/20	3/8	1633-2014
1/21	12	
1/22	10	
1/23	12	
1/24	10	
1/25	3/8	1408-1738 2145-2204
1/26	7	
1/27	10	
1/28	10	
1/29	10	
1/30	10	
1/31	2 1/2	
2/1	1/4	1250-2041, 2302-2400
2/2	1/4	0000-0033, 0517-0855
2/3	3/4	0129-0155 0229-0255
2/4	12	
2/5	2 1/2	
2/6	1/4	0148-0328 0432-1055 1209-1323
2/7	[illegible]	
2/8	10	
2/9	4	
2/10	15	

Date	Min Vis mi	Times Visibility < 1 mi
2/11/85	12	
2/12	3	
2/13	1/16	0655-0848 1439-1455, 2143-2247
2/14	5	
2/15	8	
2/16	15	
2/17	12	
2/18	12	
2/19	12	
2/20	10	
2/21	8	
2/22	10	
2/23	1/4	1724-1919
2/24	1/2	2348-2400
2/25	2	
2/26	6	
2/27	1/4	1205-1555, 1755-1822
2/28	12	
3/1	12	
3/2	1 1/2	
3/3	15	
3/4	2	
3/5	1/16	1503-1629
3/6	3/4	1614-1625
3/7	12	
3/8	2	
3/9	1	

Date	Min Vis mi	Times Visibility < 1 mi
3/10/85	12	
3/11	15	
3/12	3/4	1155-1326
3/13	12	
3/14	15	
3/15	15	
3/16	15	
3/17	5	
3/18	1/4	1325-1536
3/19	7	
3/20	10	
3/21	10	
3/22	15	
3/23	15	
3/24	15	
3/25	15	
3/26	15	
3/27	12	
3/28	7	
3/29	6	
3/30	0	0515-0930
3/31	10	
4/1	1 1/2	
4/2	4	
4/3	10	
4/4	6	
4/5	7	
4/6	2	

Date	Min Vis mi	Times Visibility < 1 mi
4/7/85	7	
4/8	1 1/2	
4/9	12	
4/10	15	
4/11	4	
4/12	3	
4/13	6	
4/14	6	
4/15	1/4	0551-1211
4/16	1/16	0210-1320
4/17	10	
4/18	15	
4/19	7	
4/20	8	
4/21	6	
4/22	1/16	0507-1440, 2138-2400
4/23	0	0000-1229
4/24	15	
4/25	1/4	2330-2400
4/26	3/4	0000-0055
4/27	10	
4/28	6	
4/29	6	
4/30	12	

approximate values of extinction coefficients (sigma) were also read from the strip charts. Incidents which resulted in sigma values of 5 or greater have been listed in Table 4-2. This table also shows, for each chosen incident, a list of the sensors which were in failure mode during this period, as determined from the Failure File described earlier (see Section 3.4), and the weather types which were predominant, as determined from the Weather File (see Section 3.5). The symbols used for weather conditions are detailed at the end of the table.

4.1.3 Selected Incidents

The tables of low visibility periods compiled from Otis weather data and strip chart data were each reviewed to determine potential incidents for investigation. The criteria used to choose the final incidents included the following:

a) The incident should have a duration of at least three hours, preferably more, so as to insure sufficient points on the scatter plots for statistical significance.

b) Extinction coefficient peaks should be fairly broad, rather than sharply peaked, i.e., the time variation in the extinction coefficients should be slow.

c) The incident should be observed by most of the forward scatter meters and transmissometers.

d) A minimum of the sensors should be in the Failure File during the incident.

TABLE 4-2. OTIS LOW VISIBILITY INCIDENTS

TIME OF INCIDENT		SIGMA (km⁻¹) (APPROX)	SENSORS OUT	WEATHER TYPES
DATE	START-STOP			
1/6/84	0000-0600	40	F15A, F15B, FG50	F
1/6-7	1700-0300	30	F15B	F, LF, RF
1/11	0600-1400	18	F15B	S, SI, RI
1/12	1700-2000	8	F15B	S
1/18-19	1900-0100	8	F15B, FG50	SF
1/19	0800-1200	5	F15B, FG50	SF
1/25	0800-1400	18	F15B	L, F
1/28	0000-0400	18	F15B	L, RF, F
1/31	1200-1600	5	F15A, F15B, FG50	SF
2/4	1200-1600	8	F15B	R, RF, LF
2/4-5	2100-0600	30	F15B	RF, F
2/5	0800-1700	20	F15B, FG50	F, RF
2/12	0400-1300	40	F15B	F
2/13	0300-1700	40	F15B	F
2/13-14	2200-1400	30	F15B, FG50 (part)	F, LF
2/14-15	2200-0400	20		F
2/15-16	2200-1000	30		F
2/24	1200-1600	15		LF
2/25	1000-1200	20		?
2/28	2200-2400	10		RF, F, LF
3/9	0600-1700	30	FG50	SF
3/11	1400-1800	18	F15B (part), FG50	SF, S
3/13	1400-1800	5	F15B (part), FG50	S
3/14	1200-1500	18	F15B, FG50	F
3/16	1100-1500	8	FG50	LF, F
3/21	0000-1200	10		LF, F
3/21-22	2100-0300	12		F, RF, LF
3/29	0300-1500	10	F15B	S, RS, RI, RF, LF
3/31/84	0100-0400	5	F15B	SF
4/6	0700-0900	10		F
4/10	2000-2300	5	X-1 (part)	S, SF
4/15	2000-2300	8		LF
4/16	0200-1100	40		F, RF
4/16	1600-2000	12	HSS2	F
4/17	0000-0900	30	HSS2	F
4/17	1000-1300	25	HSS2	F
4/18	0700-1000	8	HSS2	F
4/19	0000-0800	15	HSS2	F
4/24	0900-1700	15	HSS2	LF, RF, F
5/1	0600-0900	15	F15A	F, LF
5/4	0600-1200	8		F, RF
5/5	0000-0500	8		LF, F
5/7	0500-1100	40		F
5/8	1800-2400	15		?
5/23	0100-1000	18		F
5/26	0900-1100	8	F15B (part)	RF, F
5/26-27	1900-0200	15		F, RF
5/27	0400-0600	5		F
5/29	0700-1400	15		LF, F
5/31	1600-1800	5		R, RF
6/2	0100-0400	5		RF
6/4	0400-0900	20	X-1, X-2, Y	?
6/19	0300-0700	10		F, RF
6/19	1400-1800	5		F, RF
6/20	0000-0500	40		F
6/25	1100-1400	5		RF, R

TABLE 4-2. OTIS LOW VISIBILITY INCIDENTS (Cont.)

TIME OF INCIDENT		SIGMA (km⁻¹) (APPROX)	SENSORS OUT	WEATHER TYPES
DATE	START-STOP			
6/26/84	0600-1200	25		R
6/27	0600-1100	30		F
6/30	0100-0300	8		F
6/30	0400-1200	25		F
7/1	0200-1200	25		F
7/2	0000-1000	30		F
7/3	0800-1100	12		F
7/7	1640-1700	10		RF
7/11	0800-1200	30	F15A	F
7/18	0700-1100	5	F15A	F, RF
7/20	0700-0900	12	F15A	H
7/28	0300-0500	5	F15A	F
7/29	0500-1000	20	F15A, Y	?
8/4	0200-1300	40	F15A, Y	F
8/5	0200-1200	20	F15A, Y	F
8/6	0200-0600	5	F15A, Y	F
8/7	0600-1200	30	F15A, Y	F
8/7-8	2300-1200	40	F15A	RF, F
8/9	0000-1600	15	F15A	F, LF, R
8/10	0800-1300	12	F15A	F
8/11	0500-1200	15	F15A	F
8/12	0200-0600	10	F15A	F
8/12	0800-1400	15	F15A	F
8/12-13	2200-1100	20	F15A	F
8/13	1200-1400	5	F15A	F
8/14	0500-1200	18	F15A	F
8/15	0400-1000	25	F15A	F
8/16	0200-0500	25	F15A	F
8/28	0800-0900	5	F15A	?
9/9	0300-0700	30	F15A, FG50	?
9/10	0600-1100	25	F15A, FG50	?
9/11-12	2300-0200	10	F15A	F
9/12	0400-0700	10	F15A	F
9/14	1000-1300	5	F15A	F, H
9/14-15	2100-0100	5	F15A	RF
9/19	1000-1200	20	F15A, FG50	?
9/20	0900-1100	18	F15A, FG50	?
9/23	0740-0840	18	F15A, FG50	?
9/25	1100-1300	25	F15A	F
10/12	0000-1020	40	F15A, FG50(part)	F
10/20	0600-1500	20	F15A, Y	F, RF
10/21	0100-0500	40	F15A, Y	F
10/21-22	2100-0700	20	F15A, Y	F
10/23	0000-0200	5	F15A, Y	F
10/26-27	2300-0400	15	F15A, FG50	F
10/27	0900-1400	10	F15A, FG50	F
10/28	1500-2100	5	F15A	LF
10/29	0000-0800	20	F15A	F
11/2	0400-0800	10	F15A, FG50	F
11/5	0600-1600	18	F15A, FG50	F, RF
11/6	0000-0500	25	F15A, FG50	F
11/12	0400-0700	5	F15A, FG50	R
11/27	0600-1300	40	F15A, FG50(part), HSS2	F
11/28	0500-1200	30	F15A, FG50 (part)	H
12/6	0600-1000	5	F15A, FG50	R, S, RF
12/6	1300-1600	5	F15A	F

TABLE 4-2. OTIS LOW VISIBILITY INCIDENTS (Cont.)

TIME OF INCIDENT		SIGMA (km⁻¹) (APPROX)	SENSORS OUT	WEATHER TYPES
DATE	START-STOP			
12/10-11/84	2300-0600	20	F15A	F
12/11	0800-1600	40	F15A, FG50(part)	F
12/11	2200-2400	5	F15A, FG50	F
12/12	0200-0500	10	F15A, FG50	F
12/18	0000-1600	40	F15A	F
12/22-23	2000-0100	18	HSSA	F
12/24	0800-0900	8	HSSA	?
12/24	1100-1200	5	HSSA	?
12/28	0700-1400	10	HSSA	LF
12/28	1700-2100	12	HSSA	LF, F
1/1-2/85	1500-0200	15	HSSA	F
1/2	0300-0800	15	HSSA	F
1/2	1300-1700	12	HSSA	F
1/5	1000-1500	10	FG50(part), HSSA	SF
1/8	0700-1300	10	FG50(part), HSSA	S
1/17	1400-1800	5	FG50, HSSA	S
1/19	1600-1800	5	HSSA	?
1/20	1600-2200	10	FG50, HSSA	S
1/25	2100-2300	8	FG50(part), HSSA	?
2/1	1200-1700	10	F15A, HSSA	?
2/1	1900-2100	5	F15A, HSSA	LF, RF
2/2	0500-1300	15	F15A, HSSA	F
2/3	0100-0300	8	F15A, HSSA	?
2/6	0100-1100	10	F15A, FG50, HSSA	SF
2/13	0600-1500	15	F15A, HSSA	?
2/13	2100-2300	8	F15A, HSSA	?
2/24-25	2200-0100	12	F15A, HSSA	F
2/27	1100-1700	12	F15A, HSSA	F

TIME OF INCIDENT		SIGMA (km⁻¹) (APPROX)	SENSORS OUT	WEATHER TYPES
DATE	START-STOP			
3/5/85	1500-1700	20	F15A, HSSA	?
3/9	0300-0500	8	F15A, HSSA	?
3/11	1000-1200	15	F15A, FG50, HSSA	?
3/18	1300-1600	8	F15B, FG50, HSSA, Y(part)	?
3/30	0400-1000	20	HSS1, HSSA	F, H
4/13	0200-0700	30	HSS1, HSSA	?
4/15	0400-1200	40	HSS1, HSSA	F
4/16	0100-0800	15	HSS1, HSSA	F
4/16	1000-1400	8	HSS1, HSSA	F
4/22	0500-1500	18	HSS1, HSSA	F
4/22-23	2300-1300	30	HSS1, HSSA	F
4/25-26	2300-0100	10	HSS1, HSSA	?

WEATHER TYPES SYMBOLS

Symbol	Weather Type
F	FOG
H	HAZE
L	DRIZZLE
LF	DRIZZLE & FOG
R	RAIN
RF	RAIN & FOG
RI	RAIN & ICE
RS	RAIN & SNOW
S	SNOW
SF	SNOW & FOG
SI	SNOW & ICE
?	NOT AVAILABLE, CAN'T FIND OR NOT IMPORTANT

e) The incident should generally be able to be categorized by a single weather type.

f) The maximum extinction coefficient should be at least 5 km^{-1}. Exceptions were made to this, especially so that incidents under weather conditions other than fog could be selected. Most of the high coefficients are caused by fog.

g) Incidents should cover all portions of the test period, as evenly as possible. Exceptions were made to allow for specific analyses which required data covering a short time frame.

Using the criteria specified, a series of 60 incidents was selected for further analysis. The dates and times of the incidents selected are shown in Table 4-3, which also contains other information on the incidents. The column Days gives a day number, starting with 1/1/84 as Day 1, for plotting of time-dependent trends. The Average Wind Direction column, with values of 01-36 corresponding to the 36 ten degree sectors used by the Weather Service, shows also the time in minutes that the wind was from this general direction, and the range of wind directions during the incident. Several direction values are shown on a line when the wind direction changed during the course of the incident. The direction 00, where no range is specified, indicates that the wind speed was below the threshold of the instrument so that the wind direction has no meaning. The weather types are indicated by the same symbols used throughout this report, as shown on Table 3-3. Finally, the listed extinction coefficients are obtained from the scatter-plot analysis--the average value computed for the T500 transmissometer for all the data, and the estimated maximum value from the scatter plot itself.

TABLE 4-3. SELECTED LOW VISIBILITY INCIDENTS

Incident No.	Date (s)	Hours	Days (Starting 1/1/84)	Average Wind			Weather Types	Extinction Coeff T500 - Overall	
				Dir (00-36)	Time (min)	Range		Avg	Est Max
1	1/6/84	1500-2200	6	[illegible]	420	15-18	F	5.4[illegible]	21
2	1/7/84	0000-0400	7	22 00	35 205		RF	[illegible]	20
3	1/11/84	0700-1300	11	03	360	02-05	S	5.47	15
4	1/12/84	1600-2000	12	05	240	04-05	S	1.75	5.5
5	1/18/84	1900-2400	18	12 06	120 180	10-15 04-08	SH	2.14	6
6	1/19/84	0800-1500	19	03	420	01-03	SF	1.86	4.7
7	1/25/84	0700-1100	25	25	240	24-25	RF LF	5.[illegible]	15
8	2/4-5/84	2100-0100	35	00	240		RF	12.92	30+
9	2/5/84	0100-0800	36	01 00	254 166	34-02	F	12.37	30+
10	2/12/84	0400-1400	43	25	600	23-27	F	20.59	30+
11	2/14-15/84	2200-0400	46	13	360	12-15	F	[illegible].00	18
12	3/9/84	0700-1700	69	05	600	03-08	S, RS	14.52	50
13	3/13/84	1400-1800	73	12	240	09-13	S	1.88	3.7
14	3/21/84	0200-1000	81	06	480	04-07	[illegible]	3.26	8.3
15	4/15/84	2000-2300	106	11 35	120 60	11-12 30-05	[illegible]	2.75	6
16	4/17/84	0100-0800	108	20 00	369 51	17-25	F	16.18	30+
17	4/19/84	0000-0800	110	01	480	36-05	F	5.25	12.5
18	4/24/84	1000-1500	115	12	300	[illegible]-15	F	8.08	14
19	5/7/84	0700-1100	128	[illegible] 00	[illegible] 103	26-0[illegible]	F	15.24	30+
20	6/26/84	0300-1000	178	[illegible] 04 00	120 189 [illegible]	[illegible]-15 02-06	[illegible]	4.[illegible]	[illegible]

TABLE 4-3. SELECTED LOW VISIBILITY INCIDENTS (Cont.)

Incident No.	Date (s)	Hours	Days (Starting 1/1/84)	Average Wind			Weather Types	Extinction Coeff T500 - Overall	
				Dir (00-36)	Time (min)	Range		Avg	Est Max
21	06/30/84	0400-1200	182	25 00	401 79	19-30	F	11.13	30+
22	7/1/84	1000-1300	183	03	180	33-07	F	5.04	18
23	7/2/84	0400-1000	184	24 00	250 110	22-28	F	13.67	30
24	7/3/84	0800-1200	185	24 00	218 22	21-28	F	3.44	10.5
25	7/11/84	0800-1200	193	22 00	82 158	18-24	F	18.41	30+
26	8/4/84	0200-1300	217	35 00	44 616	29-36	F	33.25	50
27	8/5/84	0500-1200	218	26	420	24-26	F	13.78	28
28	8/7/84	0600-1200	220	23	360	19-25	F, FH	7.99	30+
29	8/9/84	1200-1600	222	06	240	04-09	F	1.87	6
30	8/12/84	0800-1400	225	06 00	310 50	05-07	F	6.03	14
31	8/13/84	0000-1100	226	05	660	03-06	F	8.36	18
32	8/14/84	0500-1200	227	04 00	74 346	02-07	F	5.85	17
33	8/15/84	0400-1000	228	23	360	17-33	F	7.54	26
34	10/12/84	0000-0500	286	25 00	216 84	24-26	GF	16.51	30+
35	10/20/84	0800-1500	294	25	420	24-27	F	12.24	23
36	10/21-22/84	2100-0700	296	19 25 00	225 360 15	18-19 23-28	F	10.42	20
37	10/26-27/84	2300-0400	300	05 00	240 60	04-07	F	7.29	16
38	10/27/84	0900-1400	301	02 00	240 60	36-04	F	3.44	6.5
39	10/29/84	0000-0800	303	25	480	24-26	F	10.79	19
40	11/5/84	0600-1200	310	15	360	13-16	F	6.24	15.5

TABLE 4-3. SELECTED LOW VISIBILITY INCIDENTS (Cont.)

Incident No.	Date (s)	Hours	Days (Starting 1/1/84)	Average Wind			Weather Types	Extinction Coeff T500 - Overall	
				Dir (00-36)	Time (min)	Range		Avg	Est Max
41	11/28/84	0500-1200	333	23 00	218 202	21-25	F	18.80	30+
42	12/11/84	0800-1600	346	03 00	288 192	36-06	[illegible]	14.02	30+
43	12/18/84	0800-1700	353	26 00	180 360	25-28	F GF FH	16.65	30+
44	12/22/84	2000-2400	357	27	240	24-29	F	6.48	18
45	12/28/84	0700-1200	363	03 00	120 180	36-05	LF	3.15	7.3
46	1/5/85	1000-1400	371	36	240	33-36	SF	4.34	7
47	1/8/85	0800-1200	374	32	240	31-34	S	4.74	7.5
48	1/17/85	1400-1800	383	29 07 00	36 131 73	28-32 06-09	S	1.54	2.8
49	1/20/85	1600-2200	386	28	360	26-30	S	2.45	8.5
50	2/1/85	1600-2100	398	04	300	03-06	RF LF	1.65	3.8
51	2/2/85	0500-1000	399	36	300	34-03	F	6.56	12.5
52	2/6/85	0500-1100	403	07	360	06-04	SF	2.70	7
53	2/24-25/85	2200-0100	421	25	180	23-26	F	3.01	9.5
54	2/27/85	1100-1700	424	25	360	24-27	F	2.21	10.5
3555	3/30/85	0500-1000	455	24 00	225 75	22-28	FH	11.87	21
56	4/15/85	0400-1200	471	20 0	360 120	18-22	F	[illegible] 74	30+
57	4/16/85	0100-0800	472	11	420	10-12	[illegible]	6.85	14
58	4/16/85	1100-1400	472	01	180	02-03	[illegible]	0.99	3.5
59	4/22/85	0500-1100	478	15 00	240 120	13-22	[illegible]	4.20	16
60	4/23/85	0100-1200	479	04 00	60 600		F	18.30	30

Detailed analysis was done on each of the 60 selected incidents. The full data set for each incident included detailed weather listings, strip charts, and scatter plots for all sensors plotted against the T500 transmissometer.

4.2 Short Term Variations in Sensor Response

The scatter plot program calculates the slope and intercept of the least squares line through the scatter-points for several ranges of sigma. In general, the slope indicates the ratio of the responses of the two instruments over that range, while the intercept would indicate zero offsets between the instruments. A study of how the slopes vary with time should therefore be indicative of how the calibration of the FSM sensor changes with time relative to the transmissometer. Normally, the full range of data is used for this analysis.

Among the 60 incidents of low visibility chosen for analysis, there are two sequences of incidents, each consisting of four consecutive days with a pure fog event. These are incidents #21-24 (6/30-7/3/84) and #30-33 (8/12-15/84). The first of these sequences is particularly attractive, since it starts only four days after the second normalization period, at which time all of the full sigma range slopes were set to 1.0. Scatter plots for each of the eight incidents compared each FSM Sensor and the T300 transmissometer to the T500 transmissometer. Additional scatter plots were run for the first sequence, comparing the FSMs to each other. The scatter plots for the HSS1 sensor compared to the T500 transmissometer for each of the eight incidents are given in Appendix E, which also includes scatter plots for the HSSA sensor compared to the HSS1 sensor for the first sequence of incidents. The slopes of the scatter plots are presented in Table 4-4 and 4-5, for sequence 1 and 2 respectively. The slope was taken from the calculation for the

TABLE 4-4. SCATTER PLOT DATA - EPISODE 1 (Based on 6/26/84 Normalization)

PERIOD / PLOT	6/30/84 0400-1200			7/1/84 1000-1300			7/2/84 0400-1000			7/3/84 0800-1200		
	CC	FRSD	SLOPE	CC	FRSD	SLOPE	CC	FRSD	SLOPE	CC	FRSD	SLOPE
HSS1 vs T500	.985	.1142	0.851	.997	.0849	1.038	.996	.0560	0.870	.993	.1064	0.921
HSS2 vs T500	.978	.1363	0.885	.997	.0863	1.060	.995	.0638	0.886	.995	.0936	0.845
HSSA vs T500	.983	.1174	0.870	.997	.0758	1.021	.996	.0559	0.875	.996	.0766	0.879
HSS2 vs HSS1	.983	.1182	1.026	.999	.0417	1.019	.995	.0646	1.016	.997	.0771	0.913
HSSA vs HSS1	.992	.0806	1.015	.999	.0504	0.981	.998	.0406	1.005	.996	.0804	0.949
F15A vs T500	.989	.0924	1.016	.997	.0898	0.994	.998	.0423	1.022	.997	.0732	1.251
F15B vs T500	.995	.0626	1.171	.998	.0688	1.157	.996	.0532	1.132	.996	.0841	1.539
FG50 vs T500	.988	.0945	1.024	.997	.0875	0.982	.994	.0679	0.969	.992	.1196	1.151
F15B vs F15A	.992	.0775	1.141	.995	.1053	1.155	.995	0.629	1.108	.998	.0626	1.230
FG50 vs F15A	.994	.0677	1.003	.999	.0508	0.988	.996	.0540	0.947	.995	.0900	0.921
X-1 vs T500	992	.0796	1.053	.997	.0763	1.045	.998	.0377	1.032	.997	.0678	1 225
X-2 vs T500	.993	.0741	1.065	.997	.0821	1.038	.999	.0354	1.049	.998	.0616	1.308
X-2 vs X-1	.998	.0376	1.011	.999	.0566	0.990	.999	.0292	1.017	.999	.0307	1.066
T300 vs T500	.997	.0510	0.953	.999	.0537	0.928	.999	.0226	0.950	.999	.0351	0.946
F15A vs HSS1	.983	.1169	1.163	.996	.0984	0.952	.996	.0567	1.171	.993	.1152	1.346
X-1 vs HSS1	.987	.0990	1.214	.999	.0407	1.006	.996	.0565	1.183	.990	.1277	1.316
F15A vs X-1	.995	.0619	0.958	.996	.0971	0.945	.999	.0302	0.989	.999	.0428	1.019

TABLE 4-5. OTIS SCATTER PLOT DATA - EPISODE 2 (Based on 6/26/84 Normalization)

PERIOD / PLOT	8/12/84 0800-1400			8/13/84 0000-1100			8/14/84 0500-1200			8/15/84 0400-1000		
	CC	FRSD	SLOPE	CC	FRSD	SLOPE	CC	FRSD	SLOPE	CC	FRSD	SLOPE
HSS1 vs T500	.998	.0430	1.173	.998	.0310	1.176	.999	.0304	1.145	.998	.0705	0.965
HSS2 vs T500	.997	.0471	1.172	.997	.0351	1.188	.999	.0365	1.140	.996	.0938	0.968
HSSA vs T500	.998	.0372	1.030	.998	.0297	1.042	.999	.0312	1.026	.998	.0614	0.844
F15A vs T500	-	-	-	-	-	-	-	-	-	-	-	-
F15B vs T500	.996	.0517	1.181	.995	.0486	1.183	.999	.0409	1.164	.999	.0478	1 165
FG50 vs T500	.997	.0452	0.975	.994	.0550	0.994	.999	.0431	.991	.999	.0545	1.031
X-1 vs T500	.997	.0497	1.021	.996	.0412	1.013	.999	.0429	1.001	.999	.0502	0.973
X-2 vs T500	.997	.0460	1.056	.997	.0396	1.052	.999	.0392	1.043	.999	.0498	1.031
Y vs T500	.987	.0997	1.054	.991	.0637	1.078	.995	.0810	1.070	.997	.0806	1.098
T300 vs T500	.996	.0509	.915	.998	.0292	0.906	.999	.0324	0.917	1.000	.0246	0.945

incidents is identified by the calendar dates, the time period and the day number starting with 1/1/84. The subsequent values in the table represent the percent change in the slope from 1.0, the value at the normalization times.

It should be noted that correlation coefficients and residual standard deviations were also checked for these incidents. In almost all cases the data (not presented here) is not as well correlated as that for the two episodes shown in Tables 4-4 and 4-5. All of the incidents are included to get as many points as possible in the subsequent figures. The scatter in the slopes was not significantly improved by eliminating incidents with poor correlation.

A plot of percent change in slope as a function of time for the HSS1 sensor is presented in Figure 4-1. The complete set of 10 Figures for all the sensors is given in Appendix F. The percent changes plotted are those between ± 40 percent, corresponding to slopes of 0.60-1.40. Larger changes are indicated by a small arrow at the edge of the plot with the value that cannot be plotted shown at the arrow. As can be seen from Table 4-6, several of the Figures show more than one slope change greater than 40 percent. The results show clearly that the instability of slopes noticed for the two episodes discussed previously is not an isolated effect. There is no evidence of any trend or drift in calibration of any of the instruments. In each case, a horizontal line at zero percent error would be a reasonable representation of the data. There is no indication that choosing different normalization incidents, or more normalization incidents, would have any major effect on these findings. The T300 vs. T500 plot (see Figure F-10) shows that the T300 response is approximately 6 percent low compared to the T500. On the other hand, the F15B, X-2 and Y sensors all appear to be on the positive side compared to the T500. The others show points reasonably well centered around zero percent change in slope.

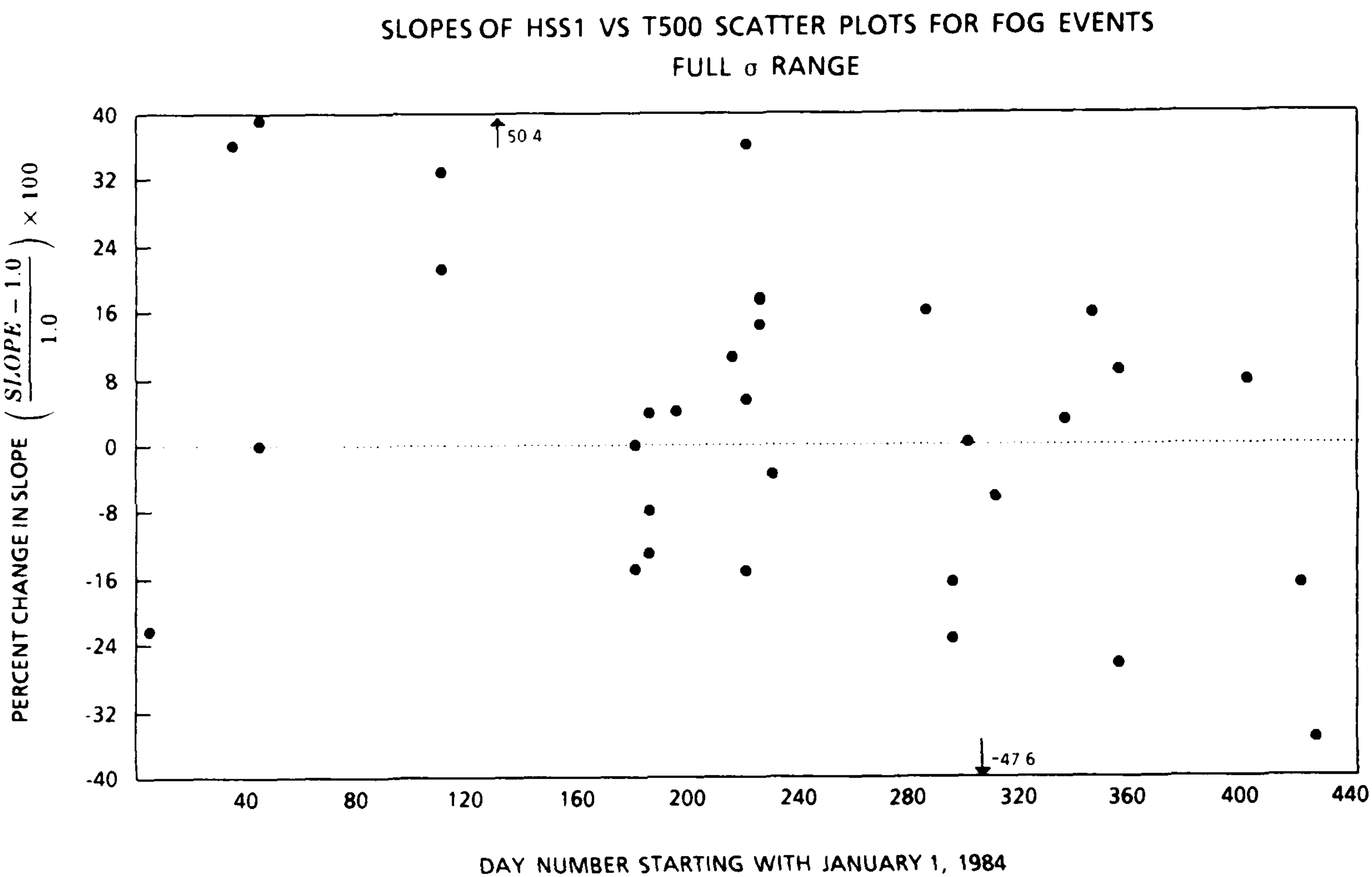


FIGURE 4-1. TIME VARIATION OF HSS1 SCATTER PLOT SLOPES FOR FULL SIGMA RANGE

The sensitivity of the scatter-plot slope plots to the selected range of extinction coefficients was investigated. It has been noted that the scatter plots often show quite different slopes when only a portion of the range of sigma is investigated. Since some of the sensors were intended for the RVR range and some for the AWOS range, it might be expected that plotting the slopes for partial sigma ranges could have an effect. The range of sigma from 3.8 to 50 km^{-1} (200-2500 feet visibility) roughly corresponds to the RVR range, and sigmas from 0.06 to 3.8 km^{-1} (0.5-30 miles visibility) to that of the AWOS range.

The analysis of slopes for the RVR range, similar to that provided for the overall sigma range, is presented in Table 4-7. The plot for the HSS1 sensor is in Figure 4-2, and the complete set of 10 plots is given in Appendix G. Similarly, for the AWOS range, data is contained in Table 4-8, Figure 4-3, and Appendix H. It is evident from all of these plots that the same general comments apply for the partial sigma range data that were noted for the full range data. There is considerable variation in the slope changes, perhaps even larger for the partial ranges, and no trends can be established. The scatter of the points might be expected to increase because slopes are obtained from fewer points for the partial ranges, and in some cases the slopes are not statistically significant.

For some of the incidents studied, it appeared that the scatter plots for sensors of a similar kind were more in agreement with each other than with the transmissometer. An additional set of comparisons was done tracing the ratios of scatter plot slopes of similar sensors as a function of time. The data is directly obtained from the previously presented slopes, i.e., the ratio of slopes HSS2/HSS1 is obtained from the slope HSS2/T500 divided by slope HSS1/T500. The analysis is

TABLE 4-7. SCATTER PLOT SLOPES FOR RVR RANGE - FOG EVENTS
(Sigma = 3.8-50.0)

	1 1 6 84 [illegible] 2200 6	2 2 5 84 [illegible] 36	3 2 12 84 0400 1400 43	4 2 14 5 84 2200 0400 46	5 4 17 84 [illegible] 0800 108	6 4 19 84 [illegible] 110	7 5 7 84 [illegible] 128	8 6 26 84 [illegible] 178	9 6 30 84 [illegible] 182	10 [illegible] 84 [illegible] 183	11 7 2 84 [illegible] 184	12 7 3 84 [illegible] 185	13 7 11 84 0800 1200 193	14 8 4 84 [illegible] 217	15 8 5 84 [illegible] 218	16 8 7 84 0800 1200 220	17 8 9 84 [illegible] 0600 222	18 8/12/84 0800 1100 225	19 8 13 84 0300 1400 226	20 8/14/84 0500 1200 227	21 8 15 84 0400 [illegible] 228
HSS1	-19.8	+36.0	+39.4	-4.9	+24.5	+33.3	+60.6	-0.5	-10.5	+3.6	-11.2	-2.2	+14.1	+17.4	-15.3	+5.5	+28.6	+17.1	+19.1	+15.0	-2.1
HSS2	-38.2	+10.7	+3.0	-4.2	-4.4	+9.4	+29.4	-1.2	-9.3	+6.4	-12.3	-19.0	+14.6	+4.6	-15.6	+3.1	+35.1	+16.1	+20.2	+13.5	-5.3
HSSA	14.8	+19.3	+10.9	-4.6	+10.0	+17.8	+50.1	-0.1	-9.9	+1.8	-10.1	-15.1	+11.4	+18.9	15.9	-4.8	+6.7	+1.6	+4.9	+2.5	-16.9
F15A	-5.2	-2.4	+11.9	-1.4	-5.2		+22.0	+1.4	+3.3	+3.4	+5.2	+18.0									
F15B				+0.2	-8.6	-7.5	+9.5	+0.3	+15.6	+18.7	+10.0	+47.1	+21.6	+46.9	+25.6	+13.0	+20.9	+17.2	+19.9	+15.1	+17.1
FG50	+20.1	+0.3	-10.1	-2.7	-15.6	-16.9	+2.7	-0.1	+2.5	-0.7	-2.5	+4.5	+5.4	+29.5	+16.4	+2.8	-7.3	-2.2	+0.7	+0.1	+3.7
X-1	-2.3	-4.6	+3.4	-0.4	-19.7	-2.6	+1.8	-0.9	+6.4	+5.1	+4.8	+16.3	+13.9	-3.3	-16.7	-27.2	+3.3	+1.2	+2.6	+0.2	-2.2
X-2	-3.1	-2.6	+3.4	0.0	-1.3	0.0	+23.1	-1.5	+6.1	+6.4	+6.1	+29.0	+16.8	+53.8	+15.8	+8.9	+12.5	+5.3	+7.0	+4.9	+4.3
Y	+2.9	+8.0	+10.8	-1.1			+16.5	+0.8	-1.0	-4.3	-4.3	+21.7	+16.3				+24.7	+7.7	+8.5	+6.3	+9.9
T300	-2.2	-3.7	+4.3	-2.9	-3.3	-8.5	+16.0	-4.5	-2.8	-5.7	-4.2	-4.8	+7.5	+40.8	-3.6	-1.9	+9.9	-6.7	-9.7	-8.1	-5.4

	22 10 [illegible] 84 0000 0500 286	23 10 20 84 0800 1500 294	24 10 21 22 84 2100 0700 296	25 10 26 [illegible] 84 2300 0400 300	26 10 27 84 0900 1400 30[illegible]	27 10 29 84 0000 0800 303	28 [illegible] 84 0600 1200 310	29 11 28 84 0500 1200 333	30 12 [illegible] 84 0800 [illegible]600 346	31 12 18 84 0800 1700 353	32 12 22 84 2000 2400 357	33 [illegible] 2 85 0500 1000 399	34 2 24 5 85 2200 0100 421	35 2 27 85 1100 1700 424	36 3 30 85 0500 1000 455	37 4 15 85 0400 1200 471	38 4 16 85 0100 0800 472	40 4 22 85 0500 1100 478	41 4 23 85 0100 1200 479		
HSS1	+17.3	-31.0	-16.3	-0.7	-5.7	-41.5	-4.7	+3.4	+12.7	+18.3	-29.5	+4.4	-16.8	-51.4							
HSS2	+21.7	+11.2	+15.7	-1.0	-6.3	+11.6	-22.4	-11.8	-9.9	-4.5	+3.1	+4.0	-7.5	-9.2	+2.4	-14.8	-9.9	-18.5	-10.9		
HSSA	+35.2	-38.0	-19.8	-13.2	-13.4	-39.4	-24.4	-9.8	-2.4	+3.9											
F15A											-1.1				+3.4	+4.7	+2.9	+6.5	+0.7		
F15B	+14.5	+160.1	+175.7	+10.7	-6.6	+4.0	+5.4	-1.5	+0.5	-6.2	+9.3	+8.9	+4.8	+7.8	+23.9	+12.0	+26.2	+26.7	+13.8		
FG50		-19.8	-11.7			+1.8		+10.2	+30.7	+2.6	+3.9	-2.2	-2.3	-6.1	-2.1	-3.0	-2.2	+2.8	-9.0		
X-1	+4.4	-10.3	5.1	+3.0	+1.7	-1.6	-1.4	-4.6	-9.7	-7.9	+1.6	-11.2	-4.2	+8.1	-5.9	-8.6	-1.3	-0.5	-3.9		
X-2	+10.3	+4.9	+10.2	+9.6	+4.3	+6.1	+6.2	-0.4	-6.0	-2.5	+9.8	-6.3	+5.7	+8.6	+7.7	+1.8	+9.6	+12.0	+7.7		
Y	16.8			+12.8	+3.1	+9.4	+8.3	+6.8	+3.3	+0.3	+15.7	+2.3	-8.2	+5.2	+3.8	+5.9	-1.9	+7.7	+3.3		
T300	+8.5	6.0	-4.4	-6.9	-7.4	-6.3	-2.8	-3.8	-5.7	-2.3	-4.2	-7.8	-9.7	-9.7	-3.1	-3.3	-1.8	-3.9	-6.7		

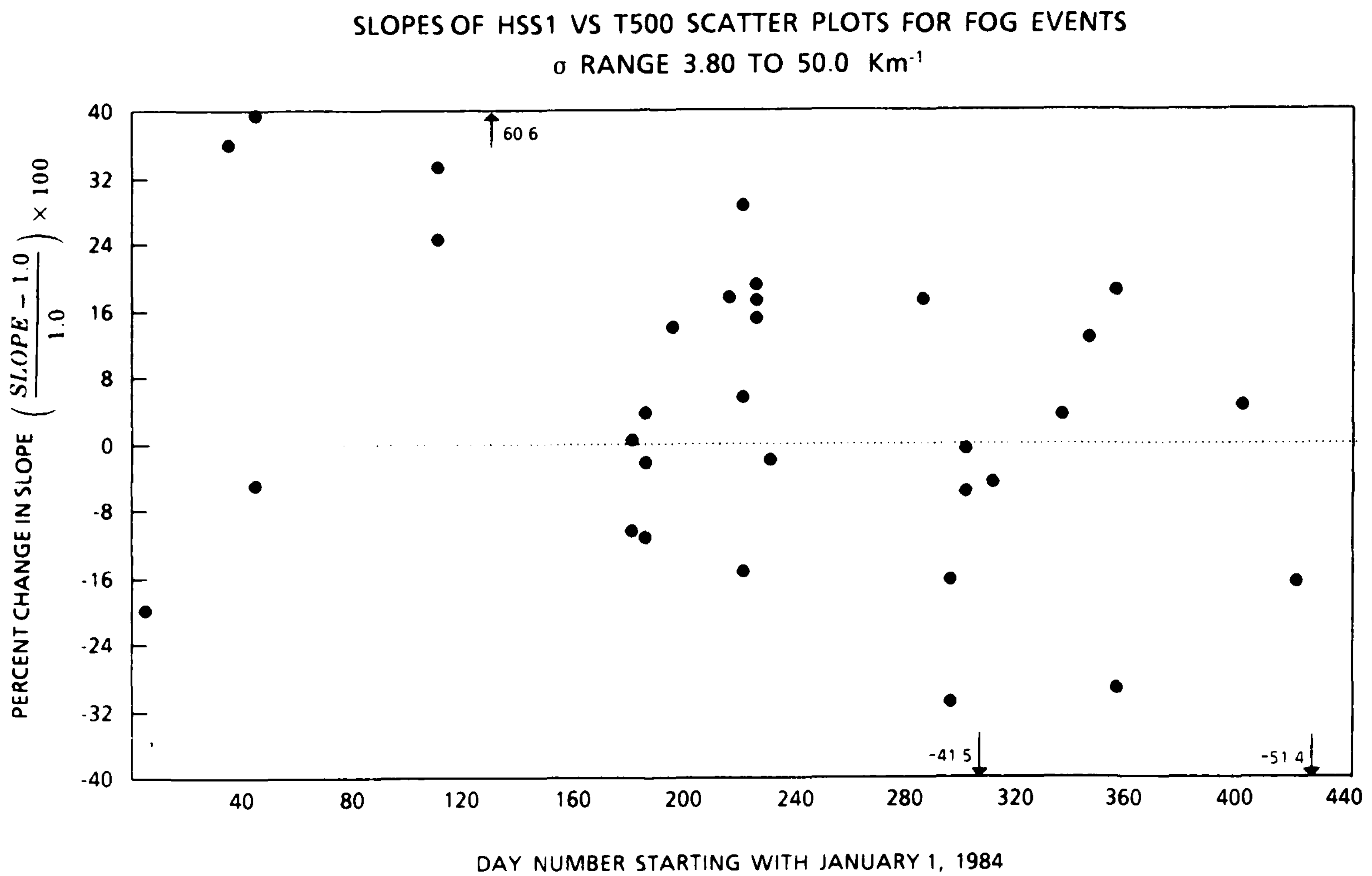


FIGURE 4-2. TIME VARIATION OF HSS1 SCATTER PLOT SLOPES FOR RVR RANGE

TABLE 4-8. SCATTER PLOT SLOPES FOR AWOS RANGE - FOG EVENTS
(Sigma = 0.06-3.80)

	1 1/6/84 [illegible] 6	2 2/5/84 [illegible] 36	3 2/12/84 [illegible] 43	4 2/14-5/84 2200 0400 46	5 4/17/84 [illegible] 108	6 4/19/84 [illegible] 110	7 5/7/84 [illegible] 128	8 6/26/84 [illegible] 178	9 6/30/84 [illegible] 182	10 7/[illegible]/84 [illegible] 183	11 7/2/84 [illegible] 184	12 7/3/84 [illegible] 185	13 7/11/84 [illegible] 193	14 8/4/84 [illegible] 217	15 8/5/84 0500 1200 218	16 8/7/84 0600 1230 220	17 8/9/84 [illegible] 222	18 8/12/84 0800 1400 225	19 8/13/84 0000 1100 226	20 8/14/84 [illegible] 227	21 8/15/84 0400 1000 228
HSS1	-41.6	+50.7	+33.3	+5.1	+15.1	+38.6	+22.7	+13.4	-20.7	+2.9	-17.5	-9.8	-13.6	-26.7	+10.4	+21.1	+36.3	+11.9	+26.7	+14.3	+5.3
HSS2	-41.0	+65.4	+14.2	-0.6	-12.1	+12.5	+9.0	+16.9	-17.5	+8.2	-15.7	-9.3	-17.4	+6.2	+23.8	+14.8	+37.9	+15.1	+31.7	+16.7	+16.0
HSSA	-26.4	+27.2	+21.8	+5.8	+1.0	+27.0	+23.2	+18.2	-17.3	+3.7	-18.1	-5.9	-1.9	-6.6	+20.0	+5.3	+29.3	+5.8	+12.8	+5.0	+2.4
F15A		-33.7	+18.2	+4.5	+6.8		+10.0	+3.9	+12.4	-3.9	+5.2	+42.2									
F15B				-10.9	+14.8	+2.1	+11.0	+2.2	+27.7	+14.1	+30.6	+76.1	+101.2	+72.3	+95.0	+63.7	+51.9	+15.7	+28.6	+22.2	+16.7
FG50		12.5	6.2	+8.6	-15.9	18.6	-7.3	+9.1	+13.5	-2.7	+8.8	+38.7	+35.7	+33.1	+63.7	+41.4	+36.4	-0.3	+12.6	-1.4	+4.5
X 1	+4.9	-2.3	+14.8	+2.5	-17.6	+2.9	+1.0	+15.8	+8.8	+4.8	+1.9	+35.2	+54.6	+3.0	+31.4	-10.2	+25.9	+1.2	+5.9	-1.0	-1.8
X 2	+6.4	-5.8	+19.3	+2.9	+12.8	+7.3	+13.6	+11.7	+8.2	+3.8	+10.8	+39.8	+51.7	+34.3	+56.6	+27.5	+25.4	+2.0	+5.9	+4.1	+1.9
Y	-14.1	-31.3	+10.8	+5.1			+160.3	+13.2	+0.3	+13.5	+14.5	+29.3	+9.7				+25.5	-4.8	+6.9	+6.6	+3.2
T300	-3.5	-7.1	-3.4	-8.3	-3.1	-9.5	-9.3	-11.3	-6.5	-9.3	-7.7	-5.1	+15.2	-16.6	-2.2	+0.4	-6.3	-11.4	-11.0	-8.7	-7.5

	22 10/[illegible]/84 0000 0500 286	23 10/20/84 0800 1500 294	24 10/21-22/84 2100 0700 296	25 10/26-27/84 2300 0400 300	26 10/27/84 0900 1400 301	27 10/29/84 0000 0800 303	28 11/5/84 0600 [illegible] 310	29 11/28/84 0500 1200 333	30 12/11/84 0800 1600 346	31 [illegible]/18/84 [illegible] 1700 353	32 12/22/84 2000 2400 357	33 [illegible]/85 0500 [illegible] 399	34 2/24-5/85 2200 [illegible] [illegible]	35 [illegible]/85 [illegible] 424	36 3/30/85 0500 1000 455	37 4/15/85 0400 1200 471	38 4/16/85 0100 0800 472	39 4/16/85 1100 1400 472	40 4/22/85 0500 1100 478	41 4/23/85 0100 [illegible] 479	
HSS1	-22.8	-10.1	-1.5	+14.8	+4.1	29.6	-17.9	+28.2	+28.2	-8.7	-18.4	+24.[illegible]	-16.1	-33.5							
HSS2	39.4	+20.5	+25.9	+9.6	9.4	+18.9	32.8	+42.2	-24.2	+5.9	+8.2	-24.2	-6.3	-7.0	-4.0	-23.9	+1.3	-19.3	+14.5	-0.8	
HSSA		10.9	3.5	+3.7	-6.2	-27.8	-24.9	-0.8	+14.6	-20.6											
F15A											+7.4				+15.9	+12.6	+23.3	-5.9	+8.4	+20.0	
F15B	17.6	+301.1	+226.0	+30.5	+11.5	+6.2	+12.5	+57.0	+11.0	+49.7	+23.2	-12.4	+9.8	+10.0	+47.3	+35.5	+50.6	+23.3	+44.2	+29.0	
FG50		+19.8	-2.0			+8.3			-69.4	+31.7	+11.8	+0.8	-2.2	-4.1	+22.9	+19.7	+21.3	-7.8	+3.1	+2.9	
X 1	50.9	+6.0	+2.5	+14.2	+7.2	+6.1	+7.7	+15.6	+1.8	+13.8	+4.8	+5.2	-7.6	+3.6	+2.2	-2.9	+7.0	+3.1	+7.4	+18.8	
X 2	44.2	+15.4	+19.3	+21.1	+12.8	+12.2	+14.0	+28.4	+9.2	+19.2	+13.9	+13.2	+3.5	+9.7	+16.5	+7.3	+20.8	+9.6	+17.8	+22.3	
Y	+366.8			+11.7	+17.4	+1.5	+13.7	+19.5	+33.9	+52.1	+16.7	+11.0	+14.4	+3.5	+122.0	-14.0	+1.9	+3.2	+138.2	+18.3	
T300	21.4	-7.1	-5.6	-8.5	-10.5	-5.7	-7.5	-9.0	-10.0	-7.9	-6.7	-7.4	-10.0	-10.6	-25.4	-7.5	-8.7	-10.7	+0.2	-5.5	

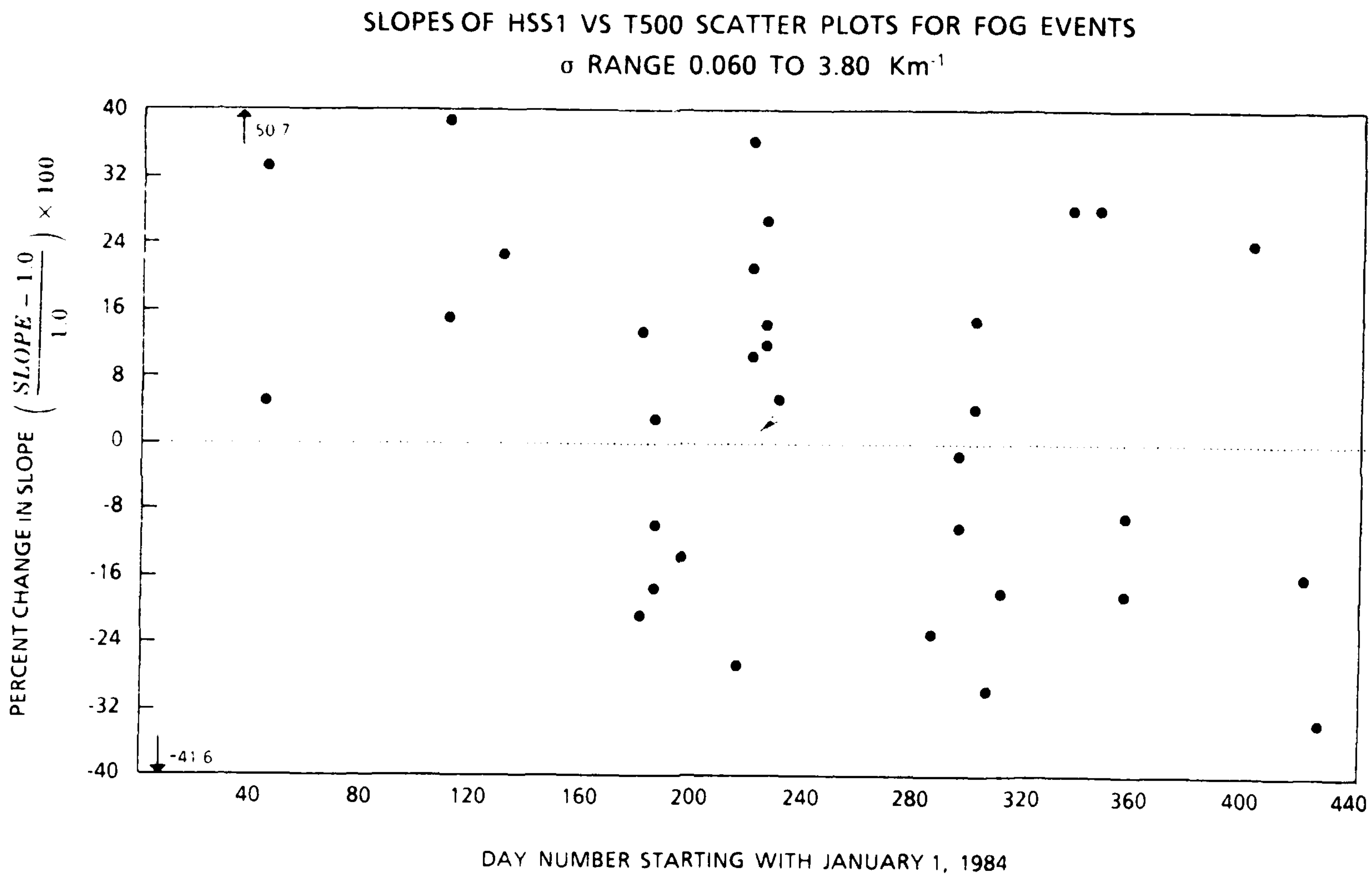


FIGURE 4-3. TIME VARIATION OF HSS1 SCATTER PLOT SLOPES FOR AWOS RANGE

presented in Table 4-9 and a plot of the HSS2/HSS1 ratios for the full sigma range is given in Figure 4-4. The complete set of nine plots is given in Appendix I. Comparing these plots to the full sigma range plots for individual sensors measured against the transmissometer (the scales are identical), there is a definite reduction of the spread of the points.

In addition to the attempt to correlate the data when slopes which had low correlation coefficients and/or high residual standard deviations were eliminated, mentioned above, several other comparisons were made. In one attempt, slopes from all of the 60 incidents were plotted, rather than just the 41 pure fog events. In general, the curves did not change much, despite the fact that the other weather conditions were added, although for several sensors the scatter did seem to increase somewhat. In another attempt, the average wind directions for each incident were superimposed on the fog event plot, to see whether any consistent pattern of specific wind directions corresponding to large slope changes could be discovered. This was hampered by the number of occurrences of wind speeds below the instrument threshhold, which made the direction readings meaningless. No general trend was observed. Finally, the average sigma values during each incident were superimposed on the fog event plot, to see whether any correlation was possible between high or low sigmas and the changes in slopes. Again, no relationship was apparent. Since none of these attempts individually had any significant effect on the plots, this data is not presented here.

Finally, to aid in understanding the physical processes which were involved in cases of large slope changes, such incidents were investigated in more detail for the EG&G sensors. Of the three FSM sensor types, the EG&G units showed the most consistent slope relationships with the transmissometer. In

TABLE 4-9. SCATTER PLOT SLOPE RATIOS FOR SIMILAR SENSORS - FOG EVENTS
(Sigma = 0.60-50.0)

	1 [illegible]/84 [illegible] 6	2 [illegible]/5/84 [illegible] 16	3 [illegible]/84 [illegible] 41	4 2/14,5/84 [illegible] 46	5 4/[illegible]/84 [illegible] 108	6 4/19/84 [illegible] 110	7 5/1/84 [illegible] 128	8 6/26/84 [illegible] 178	9 6/30/84 0400-1200 182	10 7/1/84 1000-1300 183	11 7/2/84 0400-1000 184	12 7/3/84 0800-1200 185	13 7/11/84 0800-1200 193	14 8/4/84 1200-1100 217	15 8/5/84 0500-1200 218	16 8/7/84 0600-1200 220	17 8/9/84 1200-1600 222	18 8/12/84 0800-1400 225	19 8/13/84 0000-1100 226	20 8/14/84 0500-1200 227	21 8/15/84 0400-1000 228
HSS2/HSS1	0.802	0.802	0.745	1.000	0.776	0.825	0.815	1.000	1.040	1.021	1.018	0.918	1.010	0.957	0.999	0.968	1.020	0.999	1.010	0.996	1.003
HSSA/HSS1	[illegible]	0.863	0.782	1.000	0.890	0.896	0.944	1.000	1.022	0.984	1.006	0.955	0.997	1.048	0.993	0.900	0.938	0.878	0.886	0.896	0.875
HSSA/HSS2	[illegible]	[illegible]	[illegible]	1.000	1.148	1.087	1.157	1.000	0.983	0.963	0.988	1.040	0.988	1.095	0.994	0.930	0.920	0.879	0.877	0.900	0.872
F15B/F15A				1.000	0.967		0.940	1.000	1.153	1.164	1.108	1.230									
FG50/F15A	[illegible]	[illegible]	0.933	1.000	0.887		0.846	1.000	1.008	0.988	0.948	0.920									
FG50/F15B				1.000	0.918	0.867	0.899	1.000	0.875	0.849	0.856	0.748	0.894	0.893	0.924	0.896	0.898	0.826	0.840	0.851	0.885
X2/X1	[illegible]	[illegible]	1.002	1.000	1.228	1.028	1.208	1.000	1.011	0.993	1.017	1.068	1.004	1.544	1.379	1.449	1.003	1.034	1.039	1.042	1.060
Y/X1	0.996	1.100	1.083	1.000			1.193	1.000	0.987	0.941	0.962	0.982	1.067				1.015	1.032	1.064	1.069	1.129
Y/X2	[illegible]	1.076	1.081	1.000			0.987	1.000	0.976	0.947	0.947	0.920	1.064				1.011	0.998	1.025	1.026	1.065

	22 [illegible] [illegible] [illegible]	23 [illegible]/84 [illegible] [illegible]	24 10/[illegible]/84 [illegible] [illegible]	25 10/[illegible]6/84 2300-0400 300	26 10/27/84 [illegible]-1400 30[illegible]	27 10/29/84 0000-0800 303	28 11/5/84 0600-1200 310	29 11/[illegible]8/84 0500-1200 333	30 12/11/84 0800-1600 346	31 12/18/84 0800-1700 353	32 12/22/84 2000-2400 357	33 2/2/85 0500-1000 399	34 2/24-5/85 2200-0100 421	35 2/27/85 1100-1700 424	36 3/30/85 0500-1000 455	37 4/15/85 0400-1200 471	38 4/16/85 0100-0800 472	39 4/16/85 1100-1400 472	40 4/22/85 0500-1100 478	41 4/23/85 0100-1200 479	
HSS2/HSS1	1.054	1.463	1.390	0.982	0.905	2.139	0.826	0.925	0.777	0.851	1.417	0.945	1.108	1.443							
HSSA/HSS1	1.228	0.905	0.974	0.885	0.914	1.124	0.819	0.866	0.871	0.880											
HSSA/HSS2	1.164	0.618	0.700	0.902	1.010	0.525	0.991	0.936	1.121	1.035											
F15B/F15A											1.114				1.224	1.108	1.241	1.287	1.206	1.139	
FG50/F15A											1.045				0.974	0.945	0.971	0.977	0.984	0.909	
FG50/F15B		0.305	0.315			0.952		1.064	0.929	0.987	0.938	0.925	0.915	0.862	0.796	0.853	0.783	0.759	0.816	0.798	
X2/X1	1.056	1.164	1.162	1.057	1.042	1.076	1.070	1.063	1.042	1.061	1.080	1.057	1.106	1.060	1.136	1.118	1.106	1.062	1.125	1.119	
Y/X1	0.805			1.100	1.010	1.122	1.061	1.119	1.134	1.128	1.111	1.140	1.057	1.045	1.066	1.122	1.020	0.989	1.054	1.074	
Y/X2	0.762			1.041	0.969	1.042	0.992	1.053	1.089	1.063	1.029	1.079	0.956	0.985	0.938	1.004	0.922	0.932	0.937	0.959	

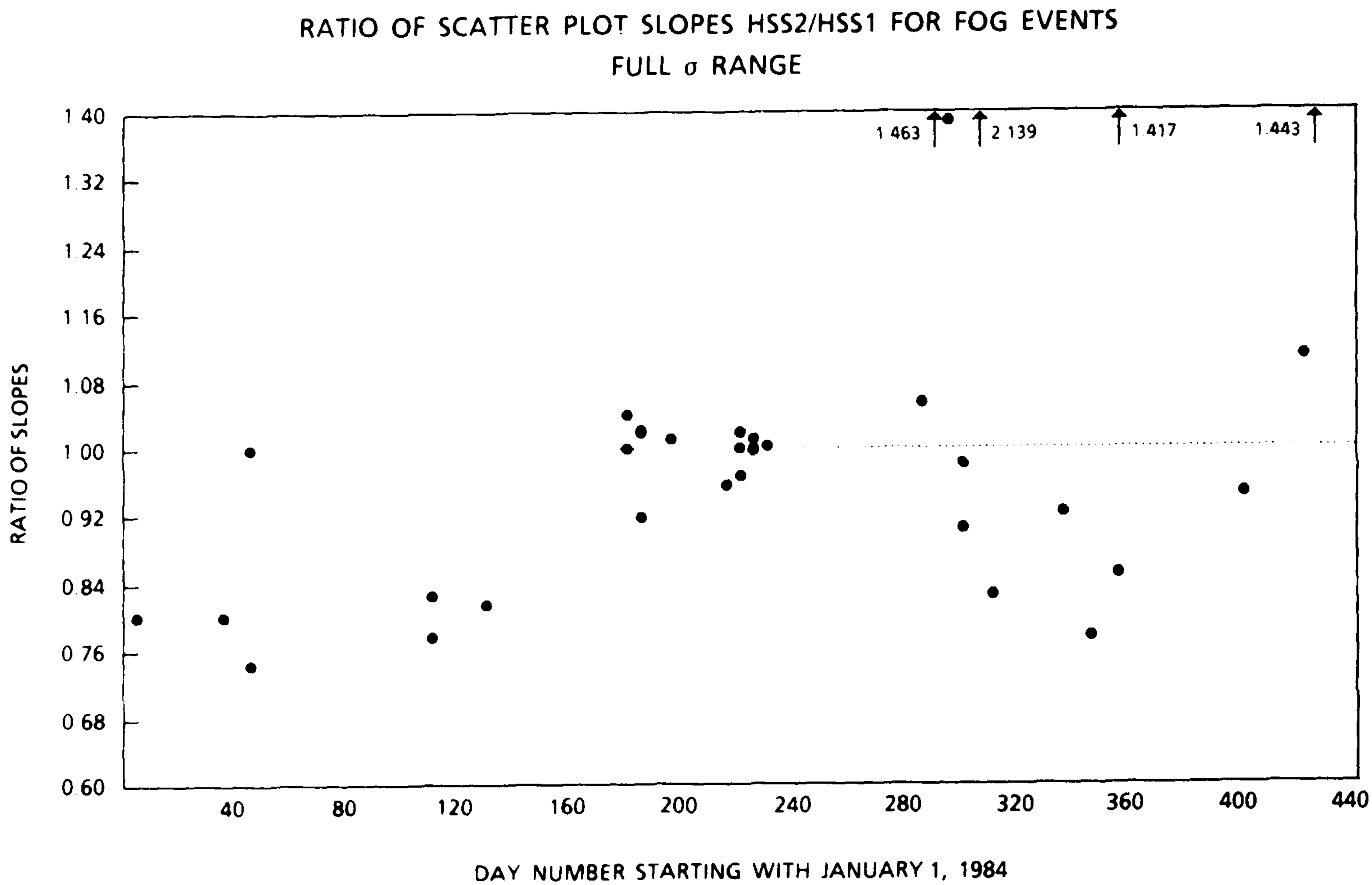


FIGURE 4-4. TIME VARIATION OF HSS2/HSS1 SCATTER PLOT SLOPE RATIOS

Table 4-6 and Figures F-7 and F-8 of Appendix F, for the X-1 and X-2 sensors, respectively, only five fog events (5, 12, 15, 16, 17 for X-1 and 7, 12, 14, 15, 17 for X-2) gave slope errors of more than 15 percent. Three of the events (12, 15 and 17) were the same for both sensors. Such slope errors represent serious disagreements between the FSM and the transmissometer for the obstruction to vision, namely fog, for which the FSMs were calibrated. Therefore, it is important to understand the conditions when such errors occur in order to assess the reliability of FSM measurements.

Two of the large-slope error events were characterized by relatively low extinction coefficients (maximum of 10 and 6 km^{-1} for Events 12 and 17, respectively). These events showed abnormally high slopes. It has been noted (References 3 and 4) that FSMs show a higher slope (perhaps 1.4) for high visibilities (haze) than for fog. Normally this high slope region lies below 1.0 km^{-1} extinction coefficient. However, for these two events the high slope region extended well above 1.0 km^{-1} and gave an overall slope just above 1.2. Apparently these summer events had very high densities of haze particles. Future research may allow a nonlinear FSM calibration that includes the effects of haze. The relative humidity could be used as a guide to differentiate haze from fog.

Two events (15 and 16) for the X-1 sensor showed a nonlinear response that showed saturation at high extinction coefficients and hence gave low slopes. This sensor was apparently defective and was shortly taken out of service.

For Event 14 the extinction coefficient went above 38 km^{-1}, so the 500-foot transmissometer saturated and gave anomalously high slopes for X-2 (but not for X-1 which also had a saturated response at that time.)

Event 7 showed a large amount of scatter (fractional residual standard deviation of 0.17) which gave an abnormally high slope for X-2 but not X-1. This result represents statistical error.

Finally, one event for each sensor (5 for X-1 and 15 for X-2) showed no anomalies. These cases had slope errors of less than 20 percent, low for the X-1 case and high for the X-2 case. Perhaps these cases represent momentary calibration changes or significantly different types of fog.

In summary, study of the scatter plot slopes indicates that the responses of each of the sensors compared with the transmissometer show large variations on a short-term basis, even when the data had just been normalized. The variations continued through the long term, but did not get larger. No long term drift in calibrations could be observed in this manner. Comparison of sensors from the same vendor showed some reduction in the variations, which indicates that the sensors agree somewhat better among themselves than with the transmissometer. Various mechanisms have been suggested as underlying the large slope variations for the EG&G sensors, which are also applicable to the other FSMs.

4.4 Transmissometer Agreement

The SENSOR analysis program, as explained previously, processes the files of extinction coefficients with the Failure File to remove from consideration all entries where either the sensor or the appropriate transmissometer is in failure mode. For the RVR range, the remaining 1-minute average extinction coefficients are used for analysis. For the AWOS range, 10-minute average extinction coefficients are formed for each period for which at least five valid coefficients exist. In both cases, the weather type is selected from the Weather File input. Fourteen categories of weather are used, plus an All-Weather grouping. For both RVR and AWOS ranges, data is rejected if the 300-foot and 500-foot transmissometer sigmas do not agree within 10 percent, and the analysis proceeds on the remaining data.

Data on the number of samples rejected ("Bad") and accepted ("Good") due to this transmissometer uniformity criterion are included on each 4-week summary SENSOR output. Since the two transmissometers occupy the same location but are crossed at right angles, this test is intended to accept only data points measured under conditions of relative atmospheric uniformity. It is also of interest to compare the response of the two transmissometers to see how often these similar instruments indicate the same extinction coefficient. The results of this comparison for the RVR range are shown in Table 4-10 for all-weather conditions, for each of the 15 four-week analysis periods. A complete set of tables for nine weather conditions and all-weather is included in Appendix J. The other five weather conditions (ice pellets, rain & ice, rain & snow, snow & ice, and snow grains) have been eliminated from this analysis as there are not enough data points to make them significant, however they are present in the summary table.

TABLE 4-10. ALL WEATHER DATA ACCEPTANCE RATES FOR RVR RANGE
(Based on Crossed Transmissometer Agreement Within 10%)

Sigma Range km-1	1.5-2.5			2.5-4.0			4.0-7.0			7.0-11.0			11.0-20.0			20.0-38.0			38.0-350.0			OVERALL		
Visability Range Feet	6500-4000			4000-2500			2500-1400			1400-900			900-500			500-250			250-30					
Period	# Bad	# Good	% Good	# Bad	# Good	% Good	# Bad	# Good	% Good	# Bad	# Good	% Good	# Bad	# Good	% Good	# Bad	# Good	% Good	# Bad	# Good	% Good	# Bad	# Good	% Good
1 26-2 3 84	368	176	32.4	152	207	57.7	223	257	53.5	105	479	82.0	105	1031	90.8	42	837	95.2	2	360	99.5	997	3347	77.1
2 23-3 22 84	492	480	49.4	127	242	65.6	169	346	67.2	321	247	43.5	500	71	12.4	139	61	30.5	1	3	75.0	1749	1450	45.3
3 22-4 19 84	212	310	59.4	323	190	37.0	166	180	52.0	102	231	69.4	117	167	58.8	37	154	80.6	9	0	0.0	965	1232	56.1
4 19-5 17 84	171	109	38.9	176	87	33.1	202	167	45.3	39	265	87.2	14	99	87.6	102	38	27.1	0	38	100.0	704	803	53.3
5 17-6 14 84	163	206	55.8	123	173	58.5	107	157	59.5	67	219	76.6	25	231	90.2	0	6	100.0	0	0	-	485	986	67.0
6 14-7 12 84	220	329	59.9	160	233	59.3	93	204	68.7	94	245	72.3	59	482	89.1	21	295	93.4	0	22	100.0	647	1810	73.7
7 12-8 9 84	123	649	84.1	129	589	82.0	60	500	89.3	21	224	91.4	17	193	91.9	8	217	96.4	0	566	100.0	358	2938	89.1
8/9-9 13 84	444	229	34.0	200	182	47.6	242	320	56.9	295	399	57.5	182	225	55.3	39	72	64.9	1	1	50.0	1403	1428	50.4
9/13-10/26/84	73	159	68.5	42	75	64.1	37	150	80.2	30	313	91.3	21	612	96.7	40	200	83.3	0	122	100.0	243	1631	87.0
10/26-11/23/84	335	169	33.5	157	223	58.7	58	236	80.3	92	334	78.4	63	283	78.7	3	6	66.7	0	0	-	708	1201	62.9
11/23-12/30/84	129	213	62.3	41	128	75.7	18	95	84.1	25	144	85.2	47	479	91.1	107	660	86.1	6	340	98.3	373	2059	84.7
12/30-1/17/85	152	401	72.5	218	391	64.2	231	448	66.0	319	220	40.8	26	135	83.9	0	0	-	0	0	-	946	1595	62.8
1/17-2/14/85	350	648	64.9	199	499	71.5	100	320	76.2	33	139	80.8	1	38	97.4	0	0	-	0	0	-	683	1644	70.7
2/14-3/14/85	87	63	42.0	34	42	55.3	48	68	58.6	21	39	65.0	8	18	69.2	5	0	0.0	0	0	-	203	230	53.1
3/14-4/11/85	46	16	25.8	51	5	8.9	33	6	15.4	6	16	72.7	8	175	95.6	0	1	100.0	0	0	-	144	219	60.3
TOTAL	3365	4151	55.2	2132	3266	60.5	1787	3454	65.9	1570	3514	69.1	1193	4189	77.8	543	2547	82.4	18	1452	98.8	10608	22573	68.0

Since the FSM sensors are not involved in this analysis, during each period for each weather condition, data from the sensor with the largest number of data points was selected.

The RVR range results are summarized in Table 4-11 for each of the weather types and ranges of extinction coefficient, for the full 60-week test period. The Total Samples column is the sum of "# bad" and "# good," and the "% good" column is an indication of how often the crossed transmissometer readings agreed within 10 percent. The last columns contain data for the overall RVR range, and show that transmissometer agreement is quite dependent on the weather type. For clarity, the information is presented graphically in Figures 4-5. The trend, clearly visible on the all-weather chart, shows that the transmissometers agree more closely as the visibility becomes lower. The agreement varies from 55 percent for visibilities in the vicinity of 1 mile to 99 percent for visibilities below 250 feet, with an overall average of 68 percent.
The poorer agreement at high visibility is probably a consequence of poor transmissometer accuracy which is not completely corrected by the transmissometer calibration process. The high agreement at low visibilities is not surprising, since for sigma values above 38 Km^{-1} the analysis makes use of the single 40-foot transmissometer instead of the crossed transmissometers and therefore defines all points as "good".

TABLE 4-11. SUMMARY OF RVR RANGE DATA ACCEPTANCE RATES
(Based on Crossed Transmissometer Agreement Within 10%)

SUMMARY FOR FULL TEST PERIOD
(1/26/84 THROUGH 4/11/85)

Sigma Range km^{-1}	1.5 - 2.5		2.5 - 4.0		4.0 - 7.0		7.0 - 11.0		11.0 - 20.0		20.0 - 38.0		38.0 - 350.0		Overall	
Visibility Range Feet	6500 - 4000		4000 - 2500		2500 - 1400		1400 - 900		900 - 500		500 - 250		250 - 30			
Weather	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good
FOG	3069	63.3	2661	66.8	3217	74.0	3006	77.4	3335	87.8	2271	91.2	1373	99.4	18932	78.1
HAZE	152	65.1	111	57.7	167	82.6	366	92.1	661	97.4	227	92.1	83	100.0	1767	89.1
DRIZZLE	14	92.9	12	91.7	13	100.0	0		1	0.0	95	0.0	0		135	27.4
FOG & DRIZZLE	1154	51.0	795	70.7	612	71.9	419	79.5	224	93.3	49	100.0	0		3253	67.1
RAIN	306	48.7	182	52.8	58	63.8	20	70.0	28	92.9	18	100.0	0		612	55.6
RAIN & FOG	1140	48.0	556	44.4	240	58.8	373	79.1	334	62.9	98	89.8	0		2741	55.8
RAIN & ICE	3	0.0	99	0.0	27	0.0	0		0		0		0		129	0.0
RAIN & SNOW	6	0.0	0		0		0		0		0		0		6	0.0
SNOW	570	54.6	282	74.1	267	42.3	305	2.0	24	0.0	2	0.0	0		1450	44.1
SNOW & FOG	616	71.1	407	61.4	452	27.2	109	68.8	110	46.4	198	30.3	12	25.0	1904	52.5
SNOW GRAIN	0		0		0		0		0		0		0		0	
SNOW & ICE	0		0		0		0		0		0		0		0	
ICE PELLETS	0		0		0		0		0		0		0		0	
OTHER	486	13.2	296	17.6	188	36.7	488	26.6	667	18.1	132	38.6	2	50.0	2259	21.6
ALL WEATHER	7516	55.2	5398	60.5	5241	65.9	5084	69.1	5382	77.8	3090	82.4	1470	98.8	33181	68.0

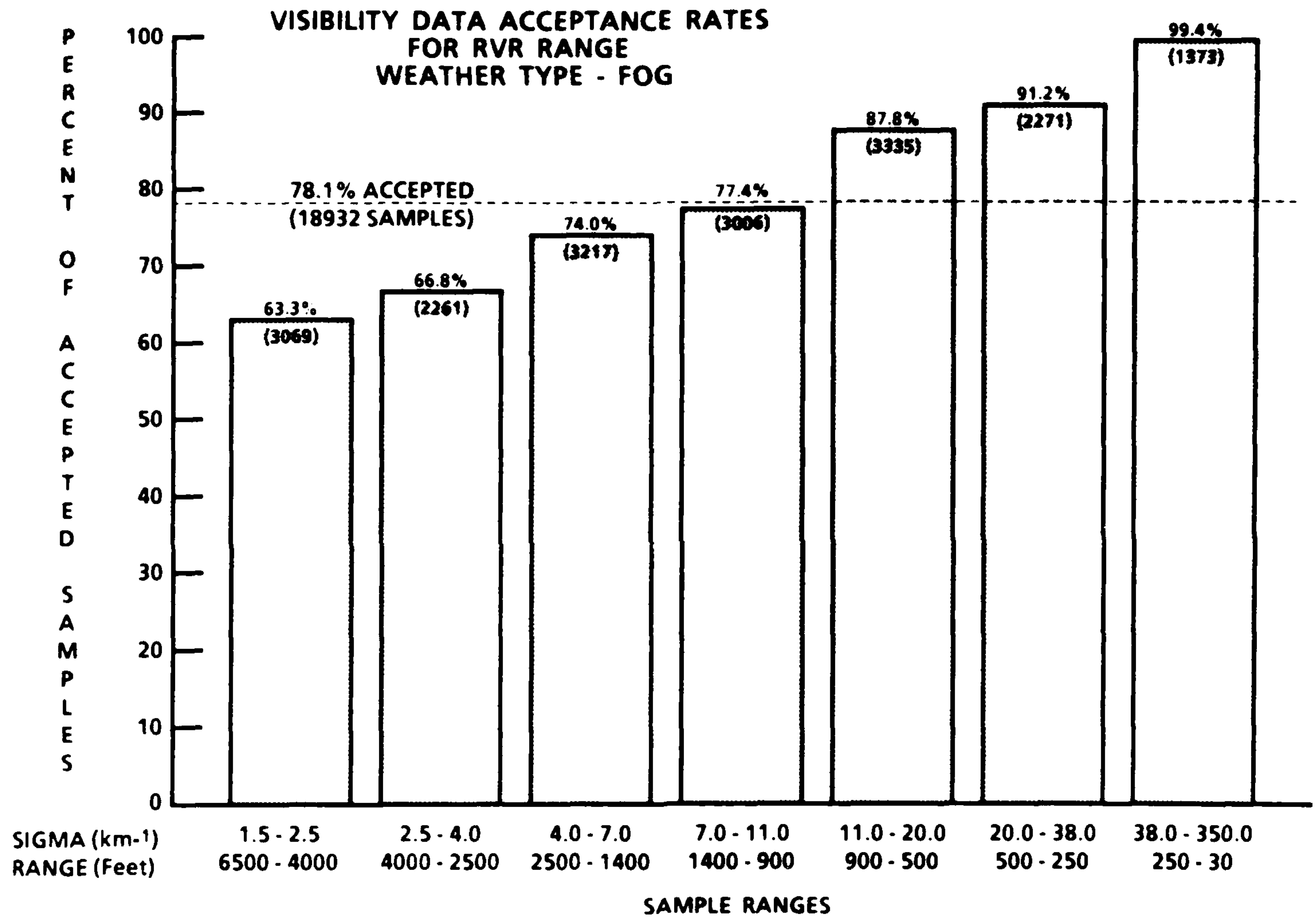


FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - FOG)

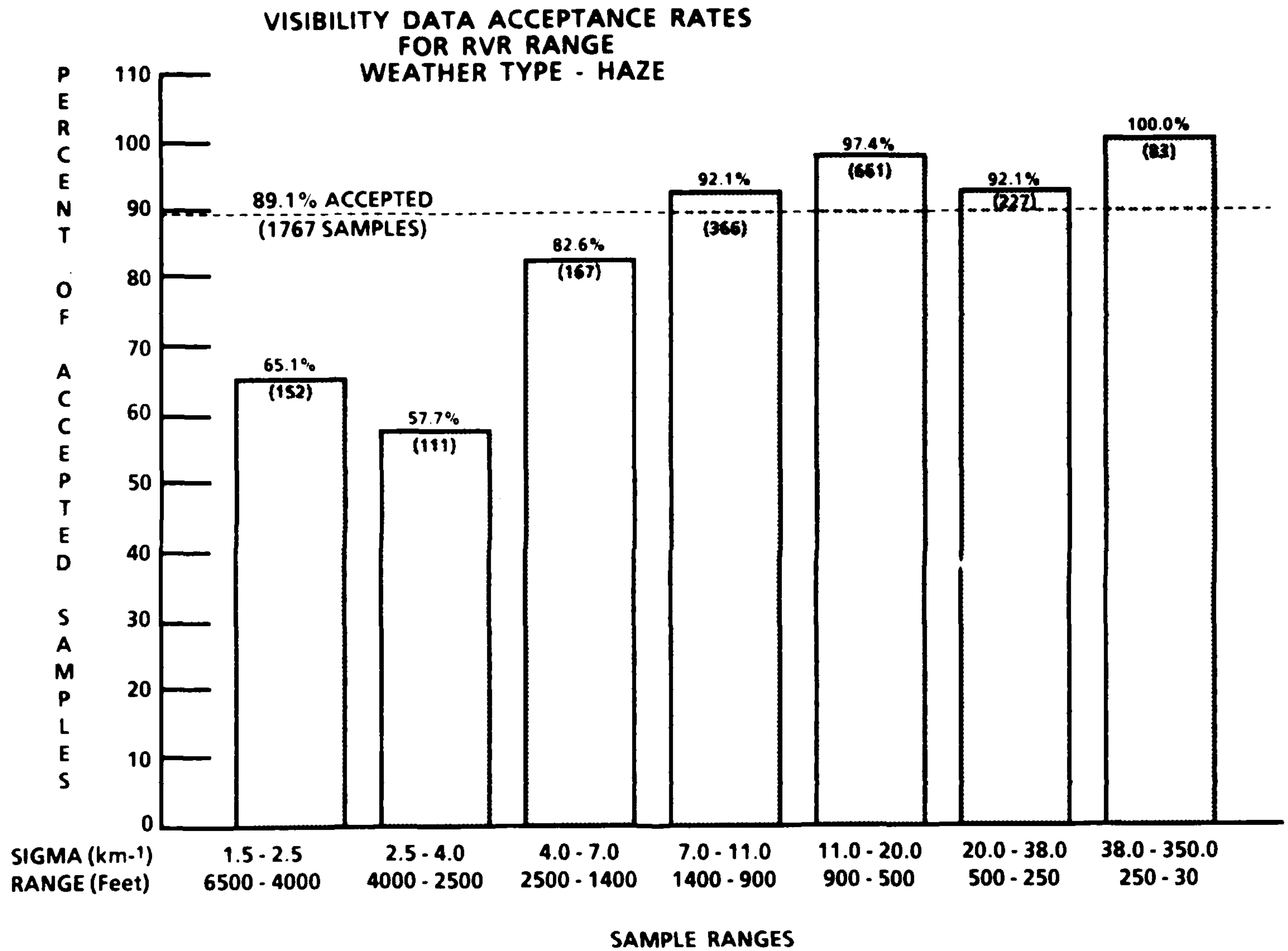


FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - HAZE) (Cont.)

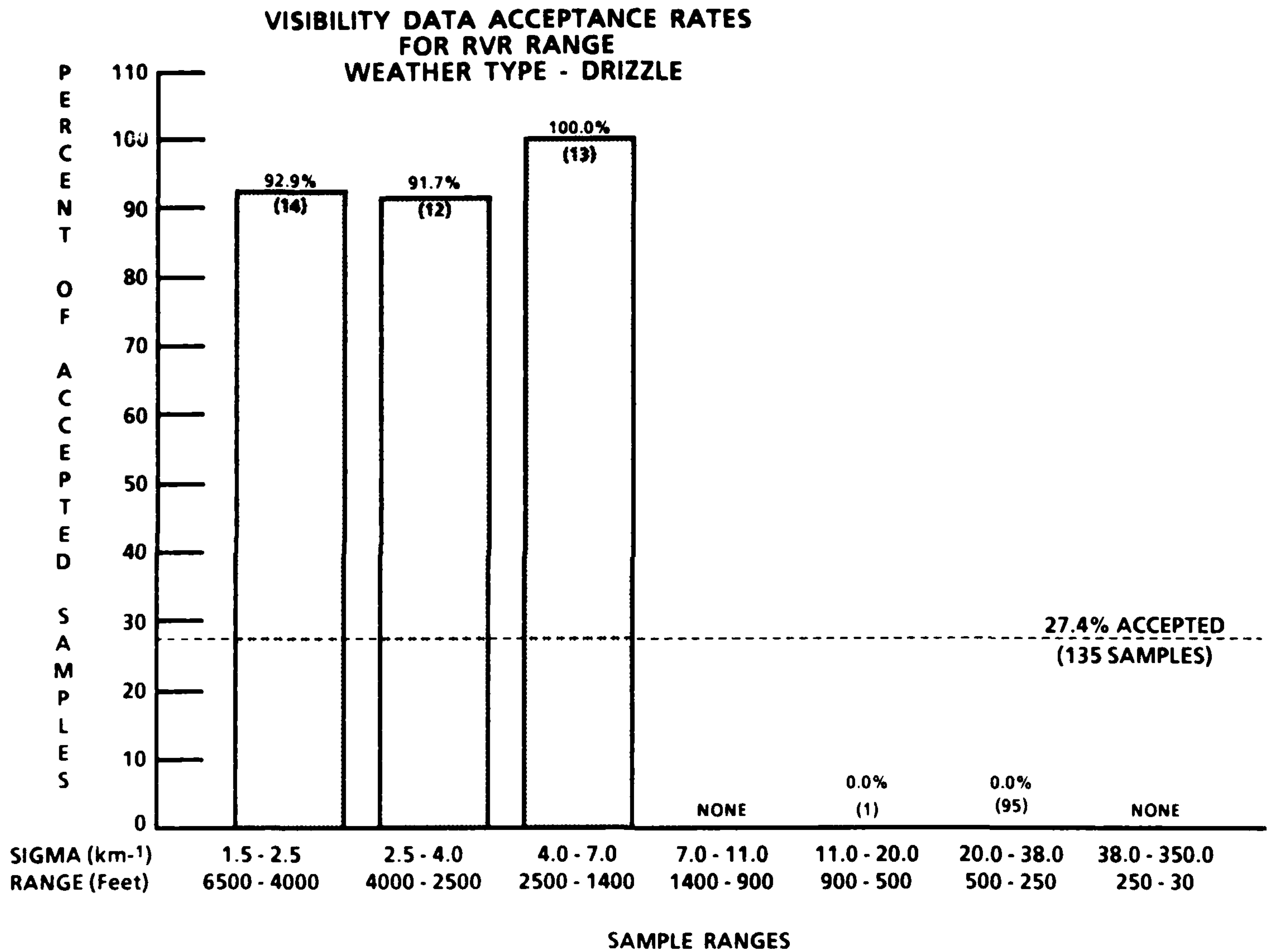


FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - DRIZZLE) (Cont.)

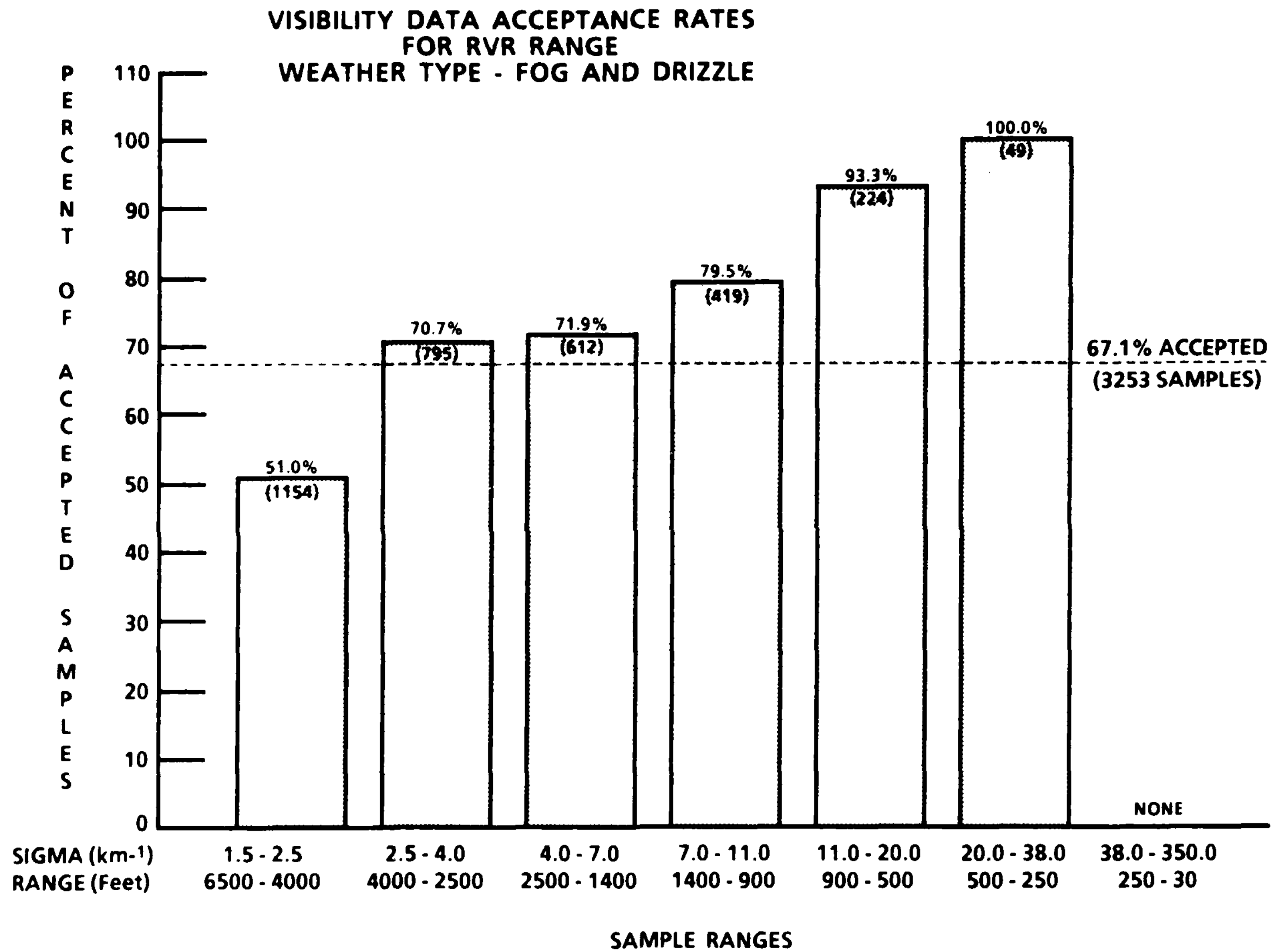


FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - FOG AND DRIZZLE) (Cont.)

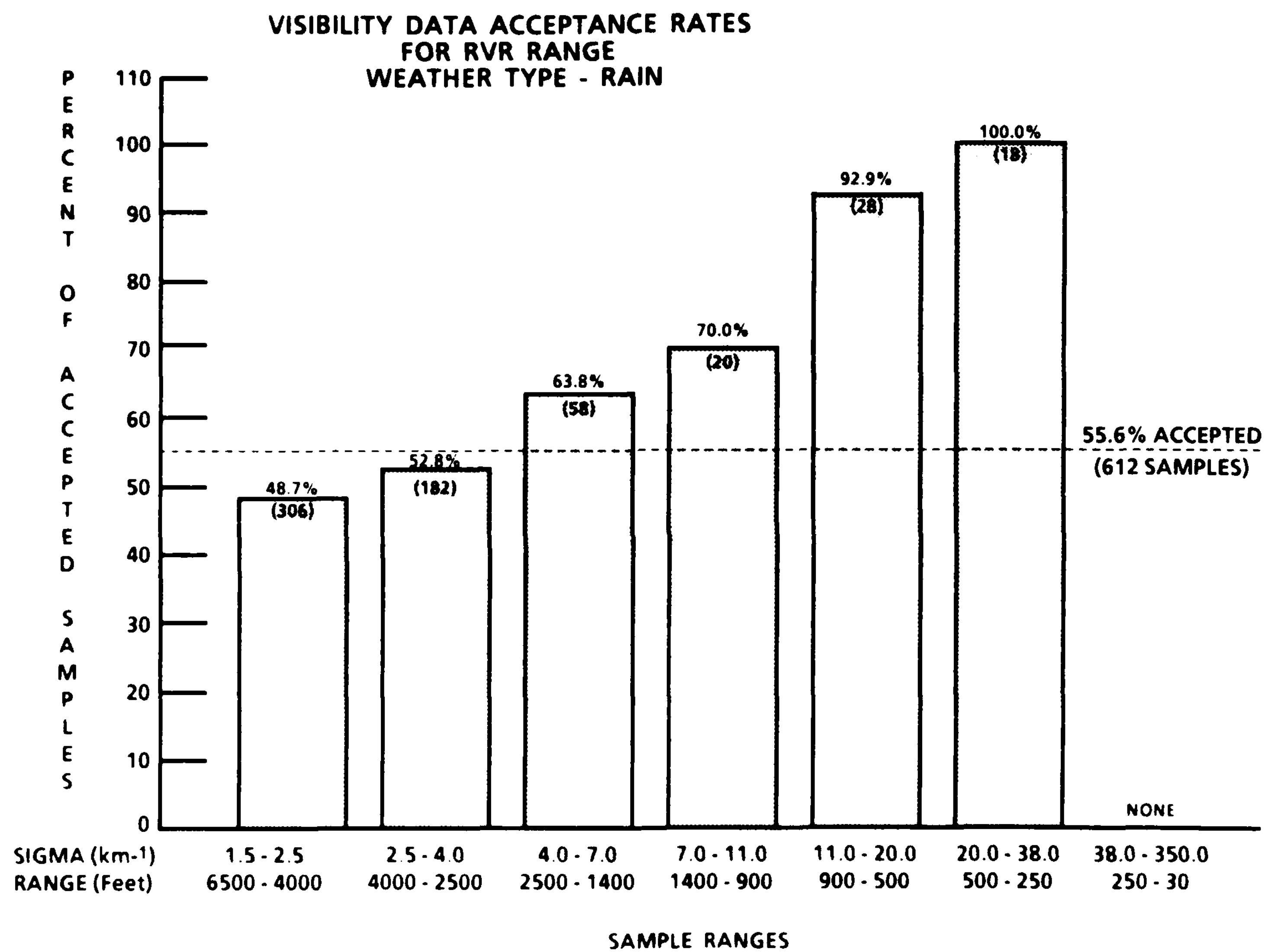


FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - RAIN) (Cont.)

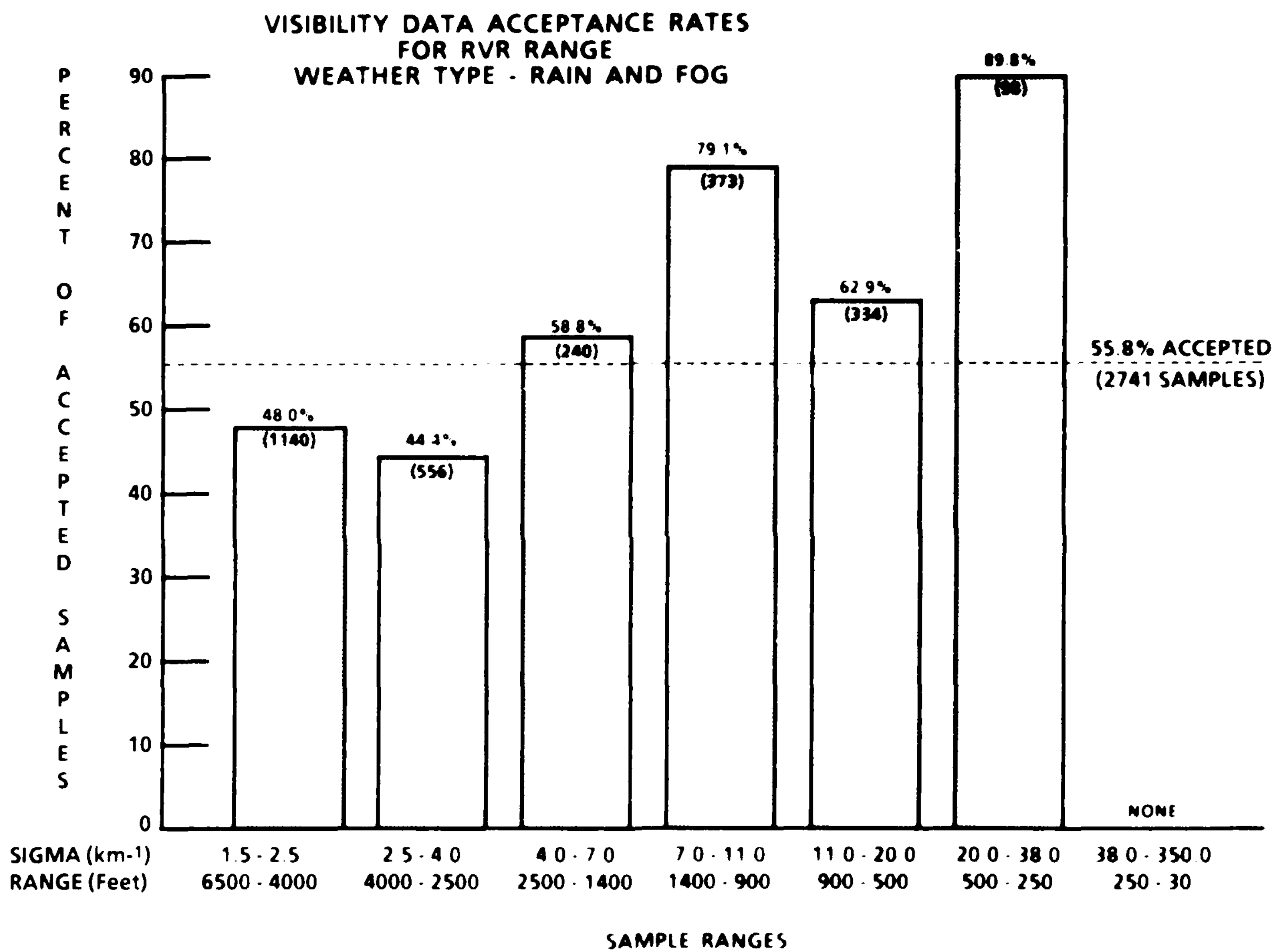
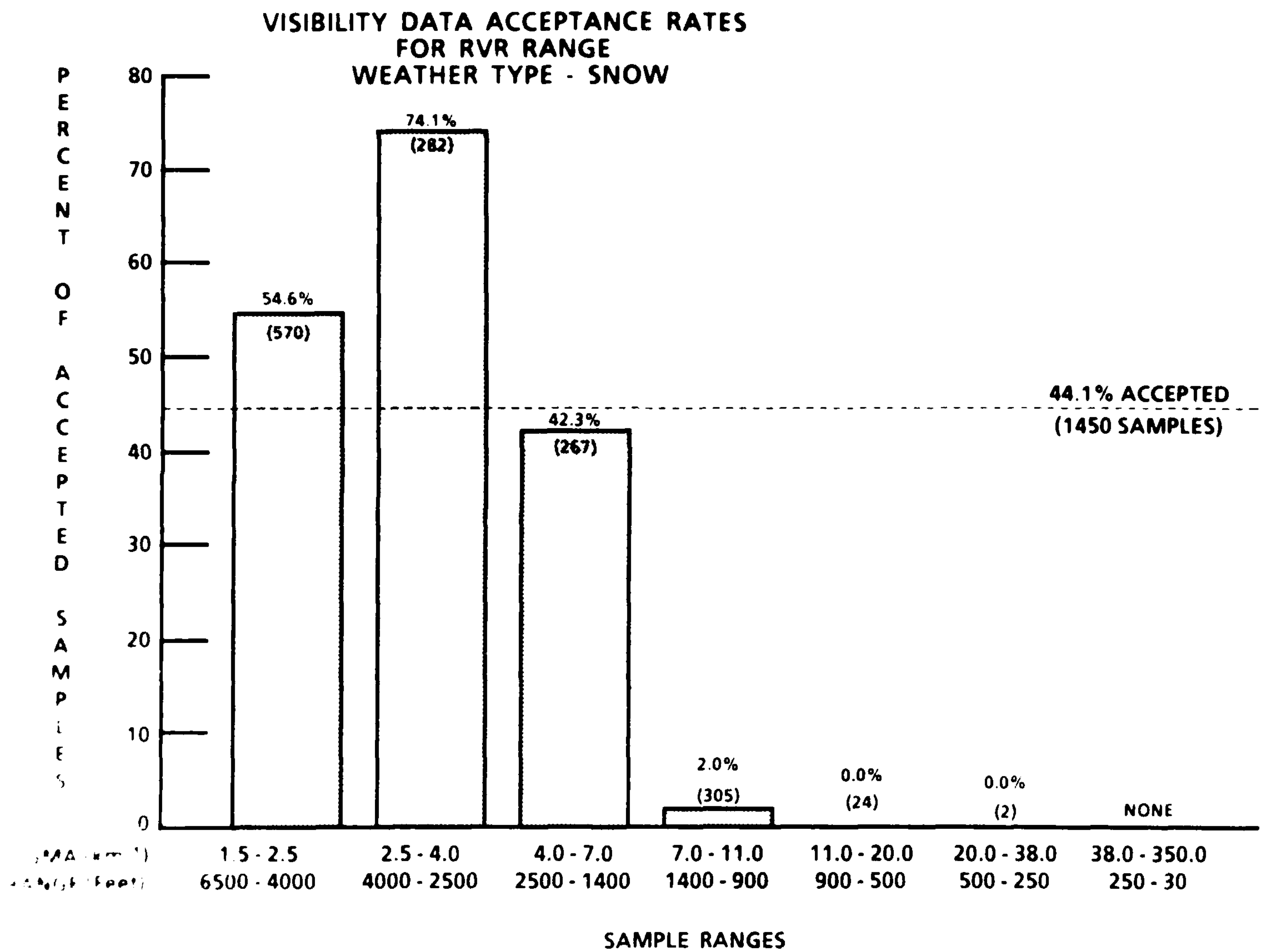
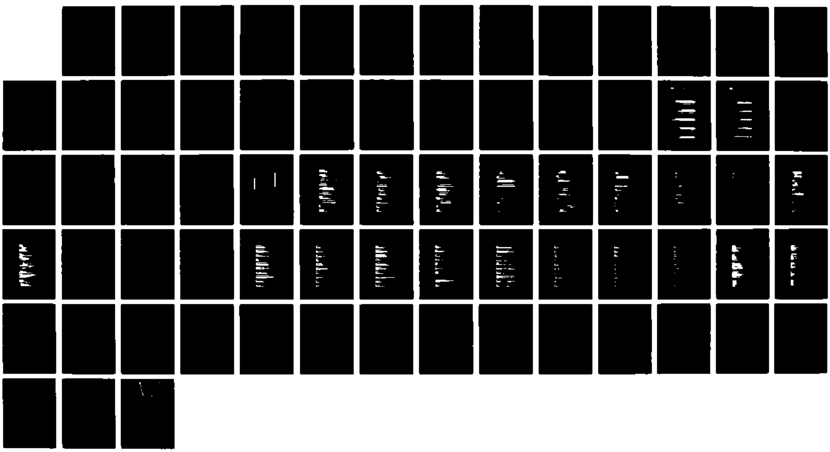


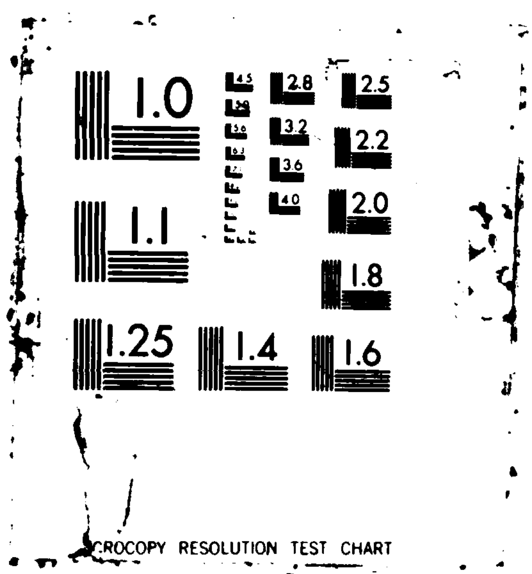
FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - RAIN AND FOG) (Cont.)



...TA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - SNOW) (Cont.)

AD-A179 176 OTIS ANGB (AIR NATIONAL GUARD BASE) VISIBILITY SENSOR 2/2
FIELD TEST STUDY(U) TRANSPORTATION SYSTEMS CENTER
CAMBRIDGE MA D SCHWARTZ ET AL. FEB 87 AFGL-TR-86-0011
UNCLASSIFIED ESD-5-606 F/G 4/2 NL




1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6
CROCOPY RESOLUTION TEST CHART

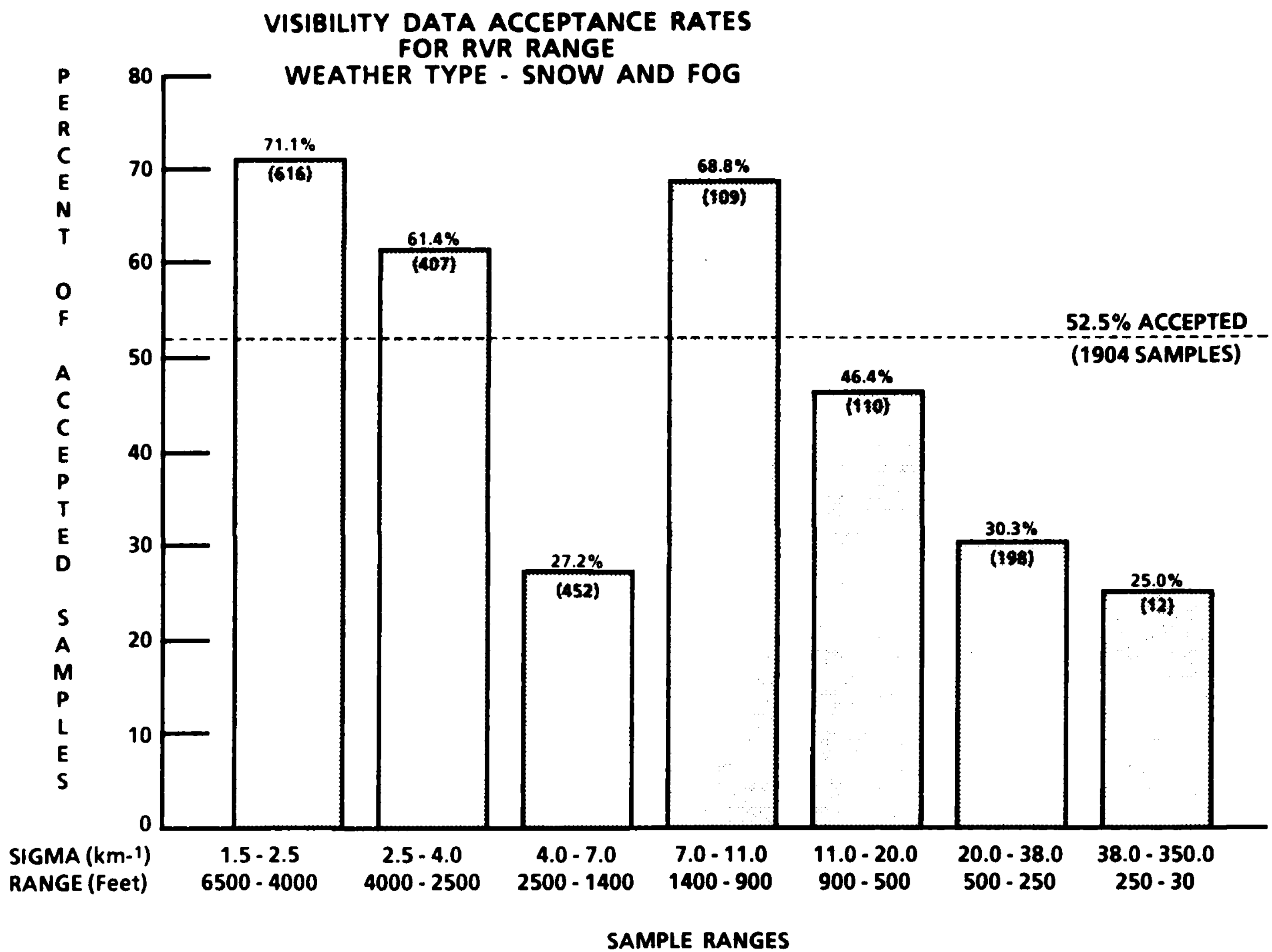


FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - SNOW AND FOG) (Cont.)

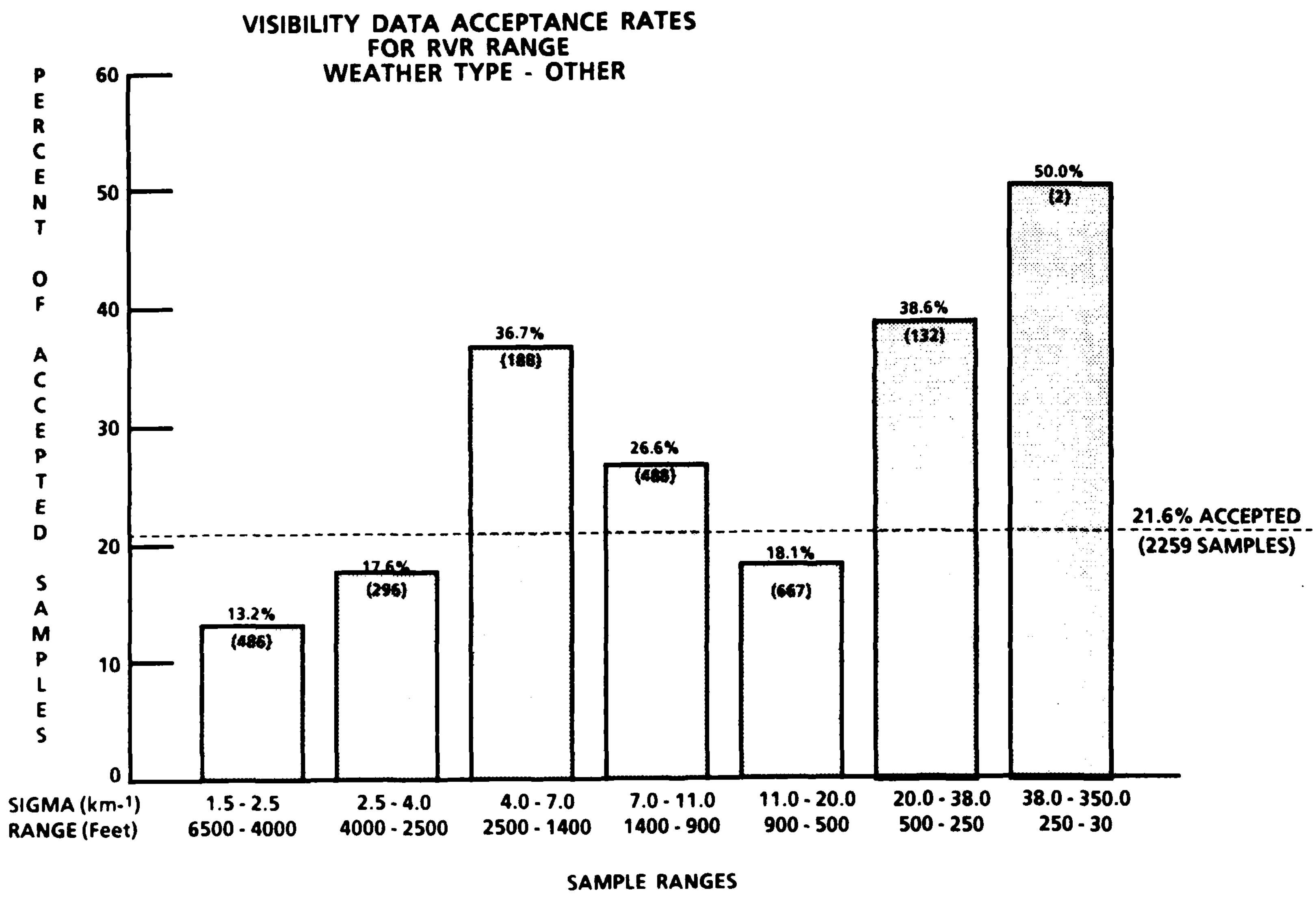


FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - OTHER) (Cont.)

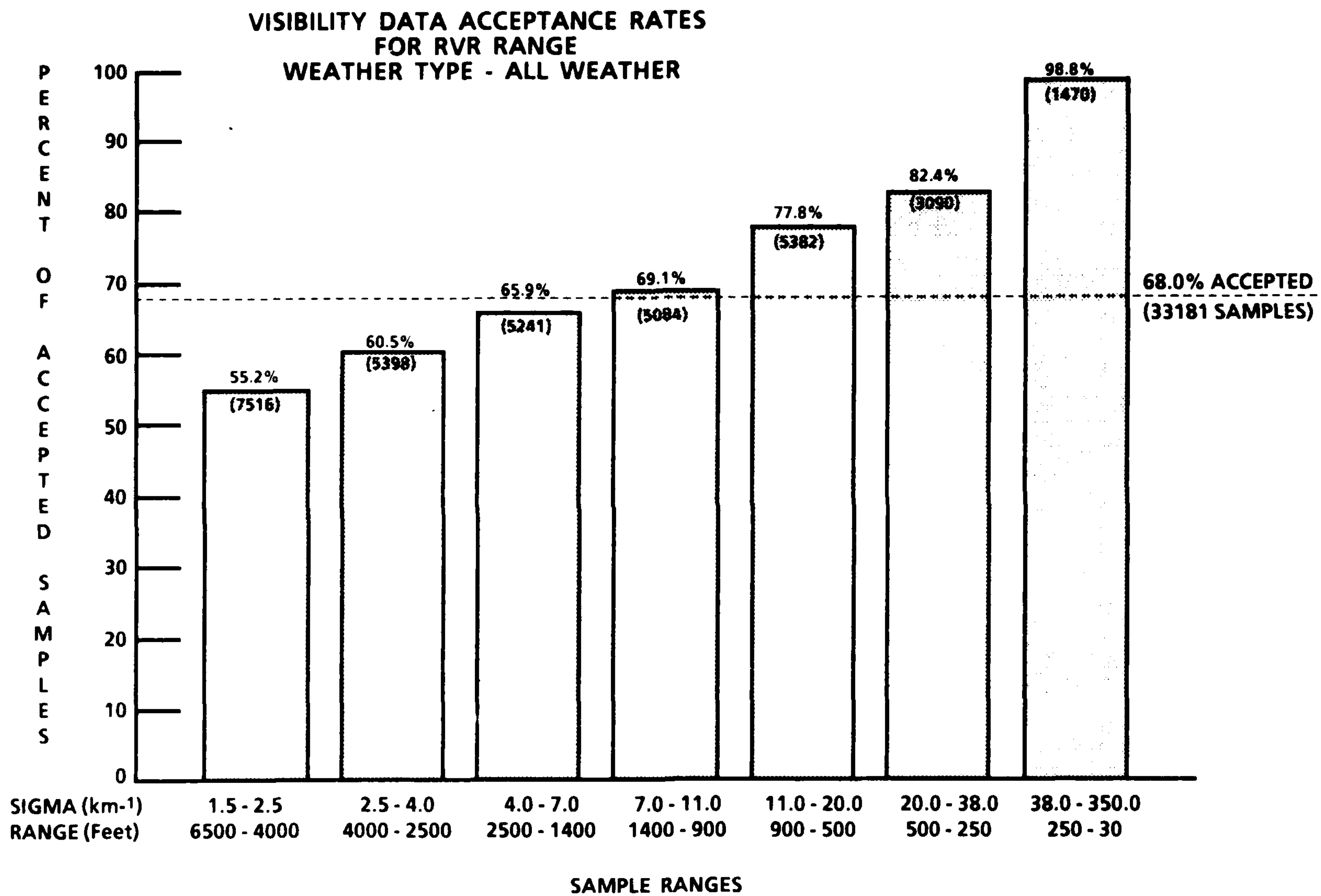


FIGURE 4-5. VISIBILITY DATA ACCEPTANCE RATES FOR RVR RANGE (WEATHER TYPE - ALL WEATHER) (Cont.)

Similar comparisons for the AWOS range are shown in Table 4-12 for the all-weather conditions. The complete set of tables as listed above is included in Appendix K. The AWOS range results are summarized in Table 4-13, for each of the weather types and ranges of extinction coefficient, for the complete 60-week test period. This information is also presented graphically in Figures 4-6. As in the case of the RVR charts, the all-weather and fog charts show that the agreement between the two transmissometers is better at lower visibilities, varying from 32 percent for visibilities of 7 or 8 miles up to 75 percent for visibilities of about half a mile. Note that visibilities of greater than 2 miles are considered to be outside the range of accuracy of these transmissometers, so that some of the poor agreement could be influenced by errors in the instruments. The overall average agreement of 45 percent is well below the overall RVR average of 68 percent.

4.5 Ratio of Sensor to Standard Readings

The analysis performed by the SENSOR program continued with all of the accepted samples, signifying relative uniformity of the atmosphere as measured by crossed transmissometer agreement within 10 percent. The program compared the sensor readings to the measurements taken with the transmissometers, used as standards. Which readings are used as standards depends on the values of the extinction coefficient. For the RVR range, the standard value is the average of the 300-foot and 500-foot transmissometers. However, when the 500-foot transmissometer indicates a sigma in excess of 38 km^{-1} (250 feet visibility and less), these transmissometers are outside their normal range of accuracy, and the standard is switched to the 40-foot transmissometer. For the AWOS range, the standard is the 1000-foot transmissometer.

TABLE 4-12. ALL WEATHER DATA ACCEPTANCE RATES FOR AWOS RANGE
(Based on Transmissometer Agreement Within 10%)

Sigma Range Km - 1	0.20 - 0.28		0.28 - 0.40		0.40 - 0.55		0.55 - 0.80		0.80 - 1.11		1.11 - 1.60		1.60 - 2.88		2.88 - 9.61		OVERALL		
Visibility Range Miles	9.00 - 6.50		6.50 - 4.50		4.50 - 3.25		3.25 - 2.25		2.25 - 1.62		1.62 - 1.12		1.12 - 0.62		0.62 - 0.19				
Period	# Bad	# Good	# Bad	# Good	# Bad	# Good	# Bad	# Good	# Bad	# Good	# Bad	# Good	# Bad	# Good	# Bad	# Good	# Bad	# Good	% Good
1/26/84 - 2/23/84	156	28	181	74	76	88	95	102	72	54	73	40	46	21	24	86	723	493	40 5
2/23/84 - 3/22/84	49	12	89	27	94	44	111	51	173	78	191	99	54	56	27	80	788	447	36 2
3/22/84 - 4/19/84	92	24	53	18	39	32	63	28	55	45	33	25	21	37	52	45	408	254	38 4
4/19/84 - 5/17/84	142	63	94	33	70	20	54	24	39	18	13	23	21	9	33	58	466	248	34 7
5/17/84 - 6/14/84	314	135	238	223	134	121	66	89	46	47	28	32	20	31	15	61	861	739	46.2
6/14/84 - 7/12/84	136	315	100	117	38	76	28	84	24	46	9	14	28	39	19	70	382	761	66 6
7/12/84 - 8/9/84	133	97	132	119	135	80	43	108	46	73	26	91	5	71	6	123	526	762	59 2
8/9/84 - 9/13/84	153	43	114	29	75	5	77	11	36	24	32	16	31	25	54	95	572	248	30 2
9/13/84 - 10/26/84	183	100	97	145	77	54	46	56	19	39	12	19	7	19	4	48	445	480	51 9
10/26/84 - 11/23/84	124	29	24	37	10	17	20	19	20	15	39	9	30	24	11	78	278	228	45 1
11/23/84 - 12/20/84	83	71	132	67	61	93	56	70	23	34	13	33	6	19	7	31	381	418	52 3
12/20/84 - 1/17/85	227	19	92	33	29	33	24	47	7	15	10	36	10	46	45	97	444	326	42 3
1/17/85 - 2/14/85	148	34	64	33	57	54	52	58	37	65	43	56	27	82	13	83	441	465	51 3
2/14/85 - 3/14/85	142	47	80	49	48	36	56	30	62	19	20	11	4	12	8	15	420	219	34 3
3/14/85 - 4/11/85	109	34	47	19	28	11	32	5	15	2	3	2	8	1	4	2	246	76	23 6
TOTAL	2191	1051	1537	1023	971	764	823	782	674	574	545	506	318	492	322	972	7381	6164	45 5
% Good	32 4		40 0		44 0		48 7		46 0		48 1		60 7		75 1				

TABLE 4-13. SUMMARY OF AWOS RANGE DATA ACCEPTANCE RATES
(Based on Transmissometer Agreement Within 10%)

SUMMARY FOR FULL TEST PERIOD
(1/26/84 THROUGH 4/11/85)

Sigma Range Km^{-1}	0.20 - 0.28		0.28 - 0.40		0.40 - 0.55		0.55 - 0.80		0.80 - 1.11		1.11 - 1.60		1.60 - 2.88		2.88 - 9.61		Overall	
Visibility Range Miles	9.00 - 6.50		6.50 - 4.50		4.50 - 3.25		3.25 - 2.25		2.25 - 1.625		1.625 - 1.125		1.125 - 0.625		0.625 - 0.187			
Weather	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good	Total Samples	% Good
FOG	947	39.6	870	39.9	558	45.5	500	55.0	336	54.5	302	59.9	338	66.9	789	81.0	4640	53.5
HAZE	607	36.2	607	47.9	272	39.7	105	83.8	38	81.6	24	83.3	16	87.5	42	90.5	1711	47.3
DRIZZLE	67	23.9	20	35.0	12	75.0	7	14.3	11	54.6	5	80.0	1	100.0	1	100.0	124	36.3
FOG & DRIZZLE	79	35.4	137	44.5	158	46.2	249	32.9	263	48.4	244	45.9	116	60.3	159	79.9	1405	47.5
RAIN	285	38.6	161	39.1	129	41.1	90	53.3	42	45.2	20	40.0	38	47.4	17	64.7	782	42.2
RAIN & FOG	221	32.6	354	41.5	376	48.4	454	48.0	410	42.7	262	43.5	119	51.3	87	72.4	2283	45.2
RAIN & ICE	0		0		0		0		0		0		1	0.0	13	0.0	14	0.0
RAIN & SNOW	1	0.0	3	0.0	0		0		0		1	0.0	1	0.0	0		6	0.0
SNOW	53	39.6	52	48.1	55	54.6	49	36.7	47	34.0	56	46.4	63	60.3	73	35.6	448	44.6
SNOW & FOG	16	18.8	38	29.0	63	42.9	62	51.6	45	53.3	55	61.8	84	64.3	66	56.1	429	51.8
SNOW GRAIN	5	40.0	0		0		0		0		0		0		0		5	40.0
SNOW & ICE	0		0		0		0		0		0		0		0		0	
ICE PELLETS	3	0.0	0		0		0		0		0		0		0		3	0.0
OTHER	958	21.3	318	22.3	112	25.0	89	22.5	56	10.7	84	8.3	33	30.3	47	63.8	1697	22.2
ALL WEATHER	3242	32.4	2560	40.0	1735	44.0	1605	48.7	1248	46.0	1051	48.1	810	60.7	1294	75.1	13545	45.5

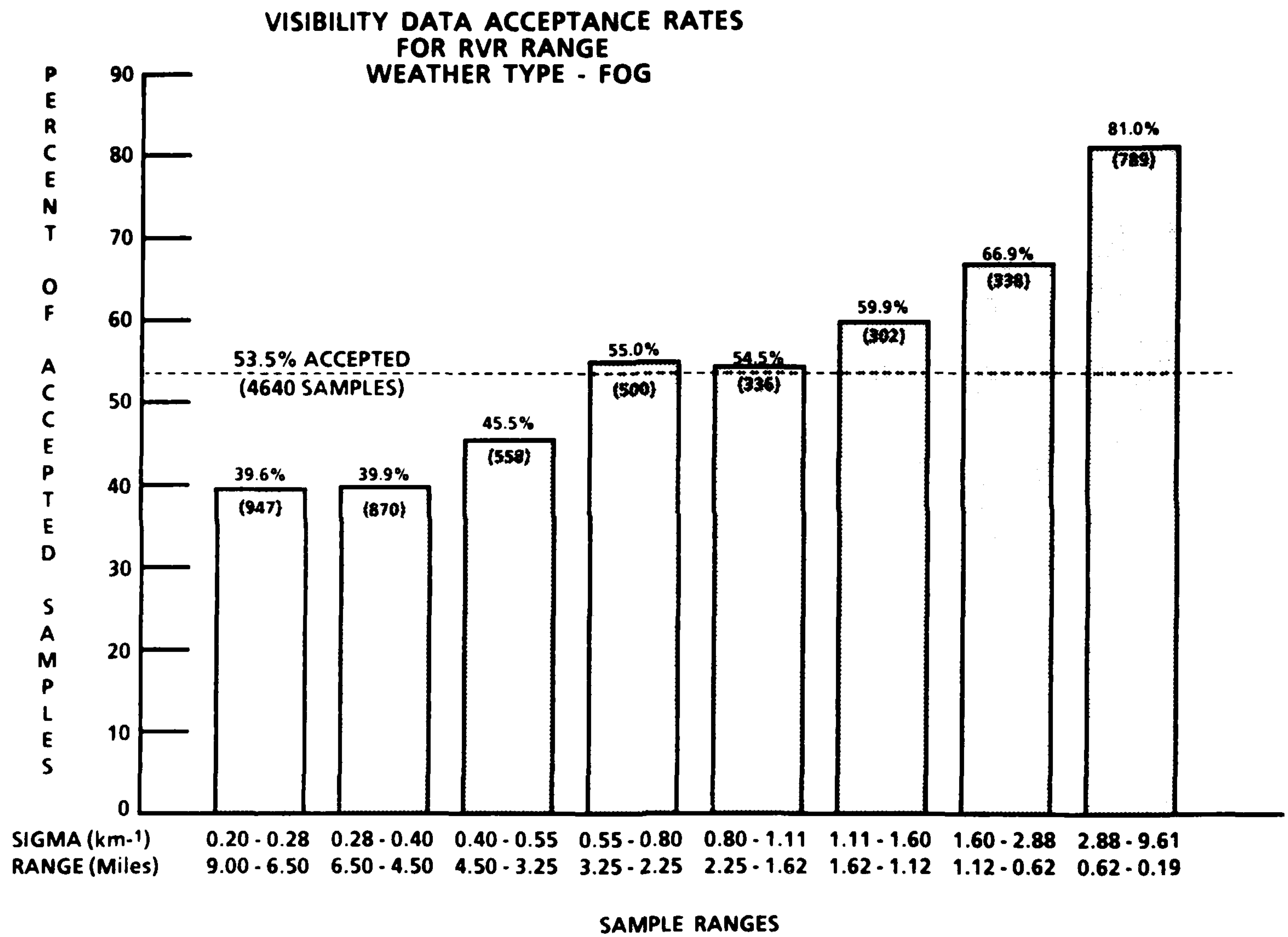


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - FOG)

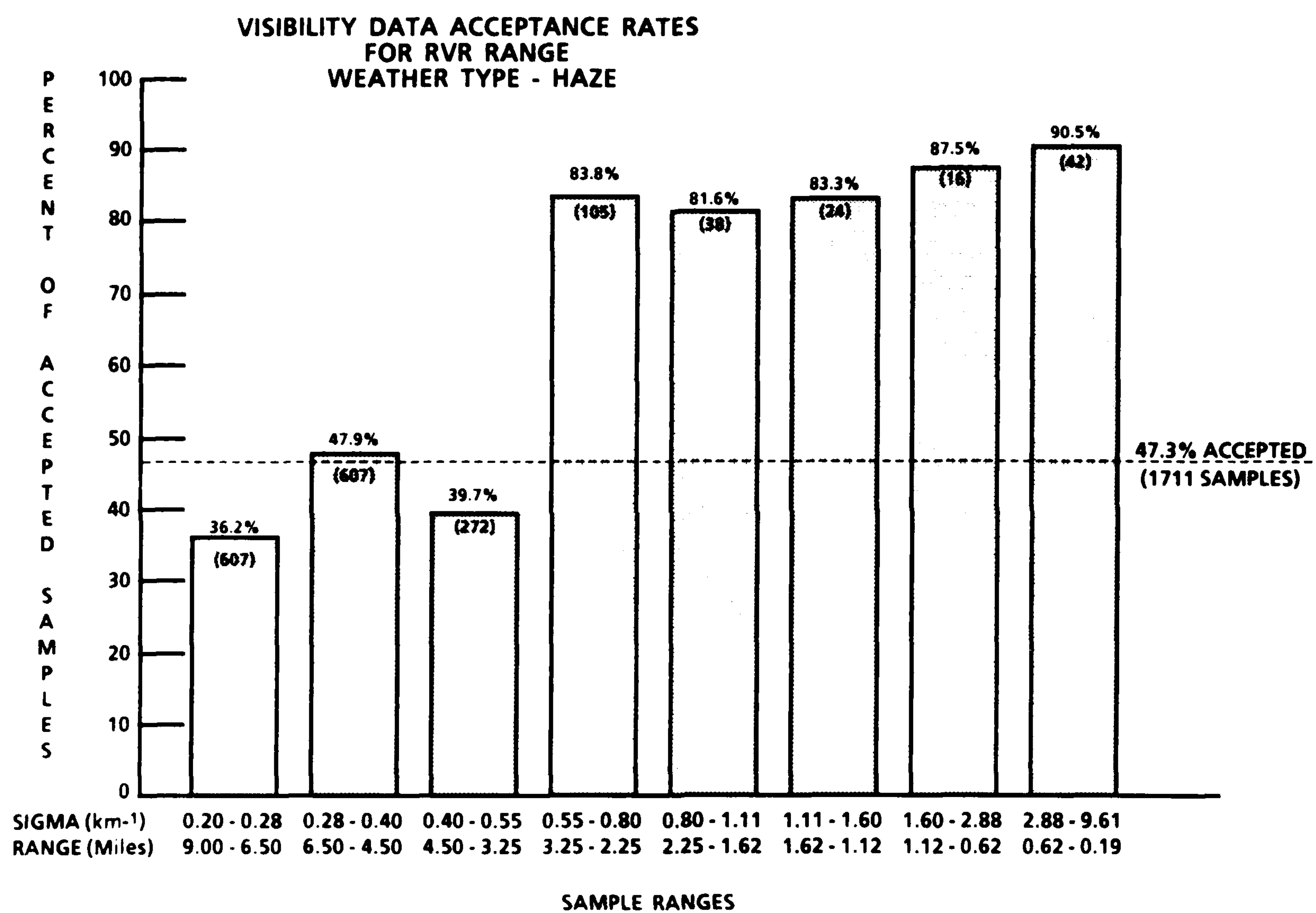


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - HAZE) (Cont.)

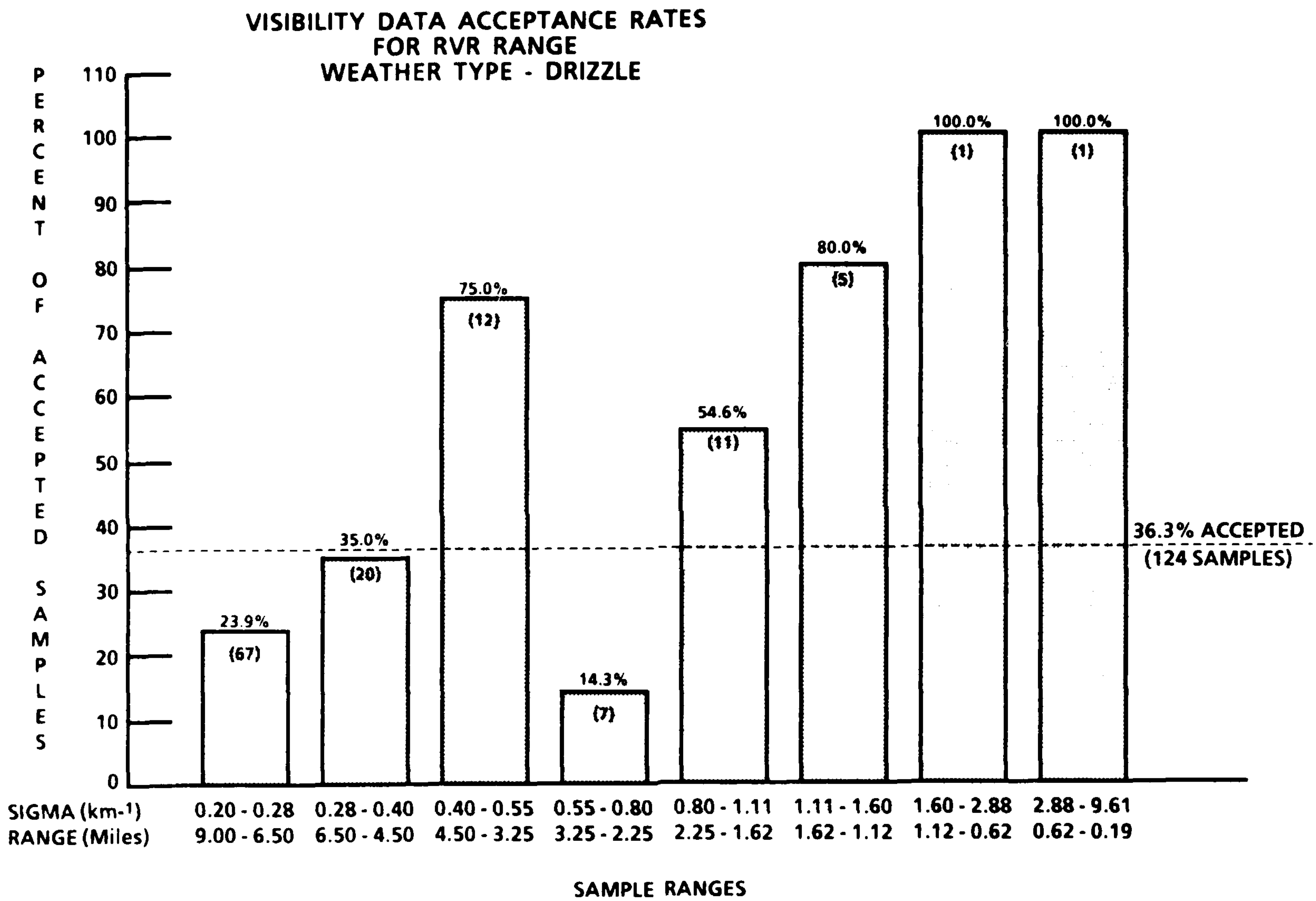


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - DRIZZLE) (Cont.)

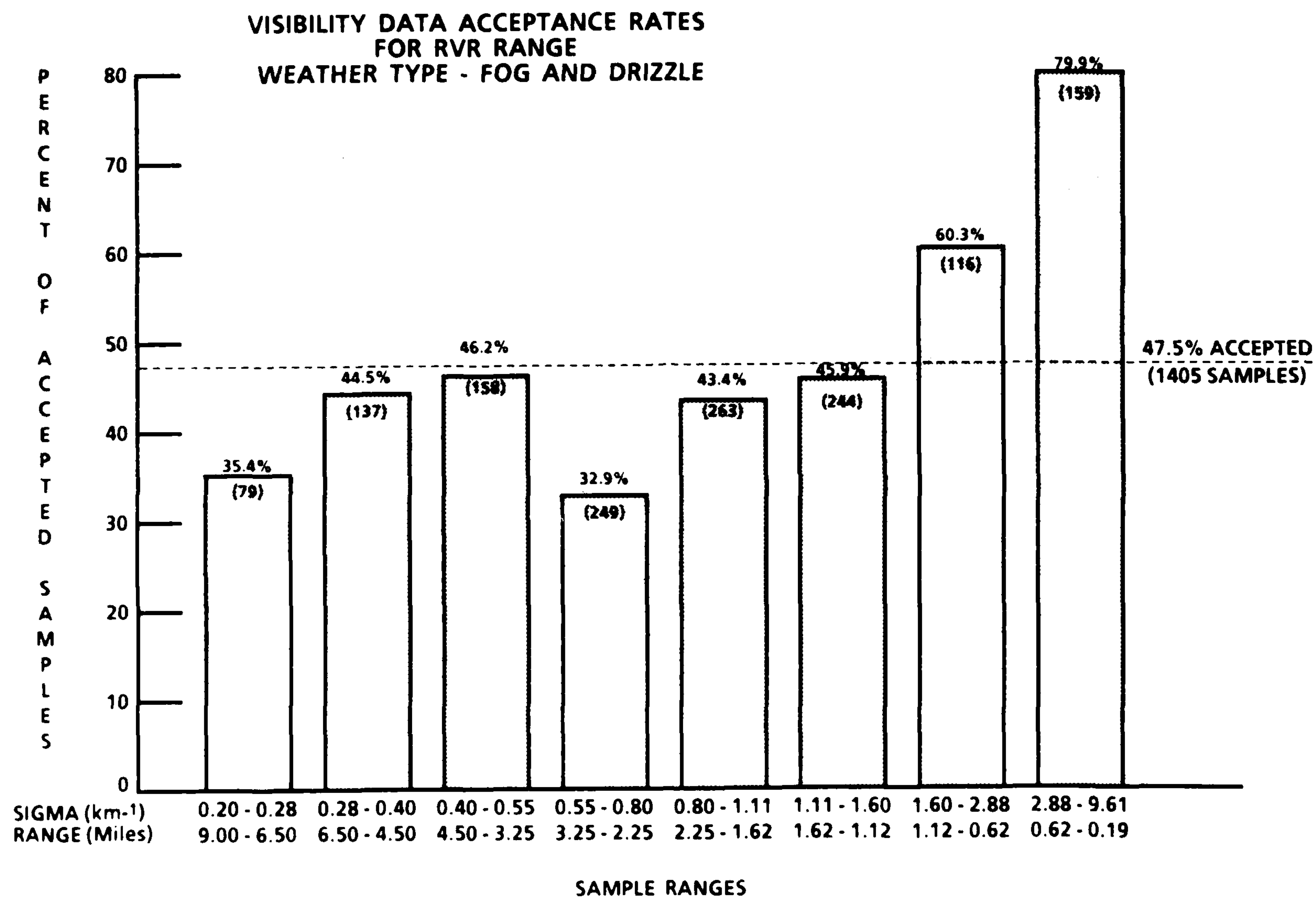


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - FOG AND DRIZZLE) (Cont.)

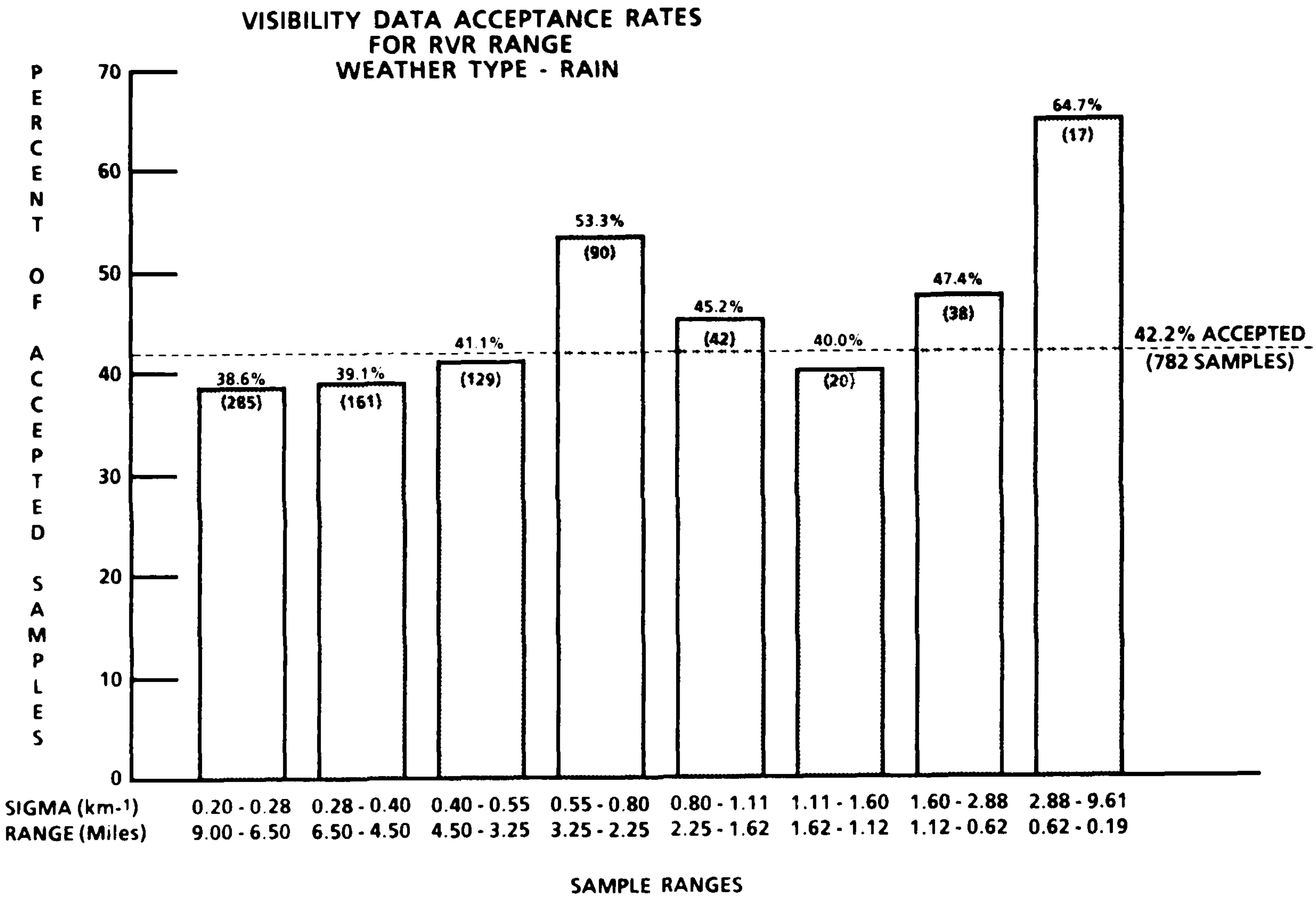


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - RAIN) (Cont.)

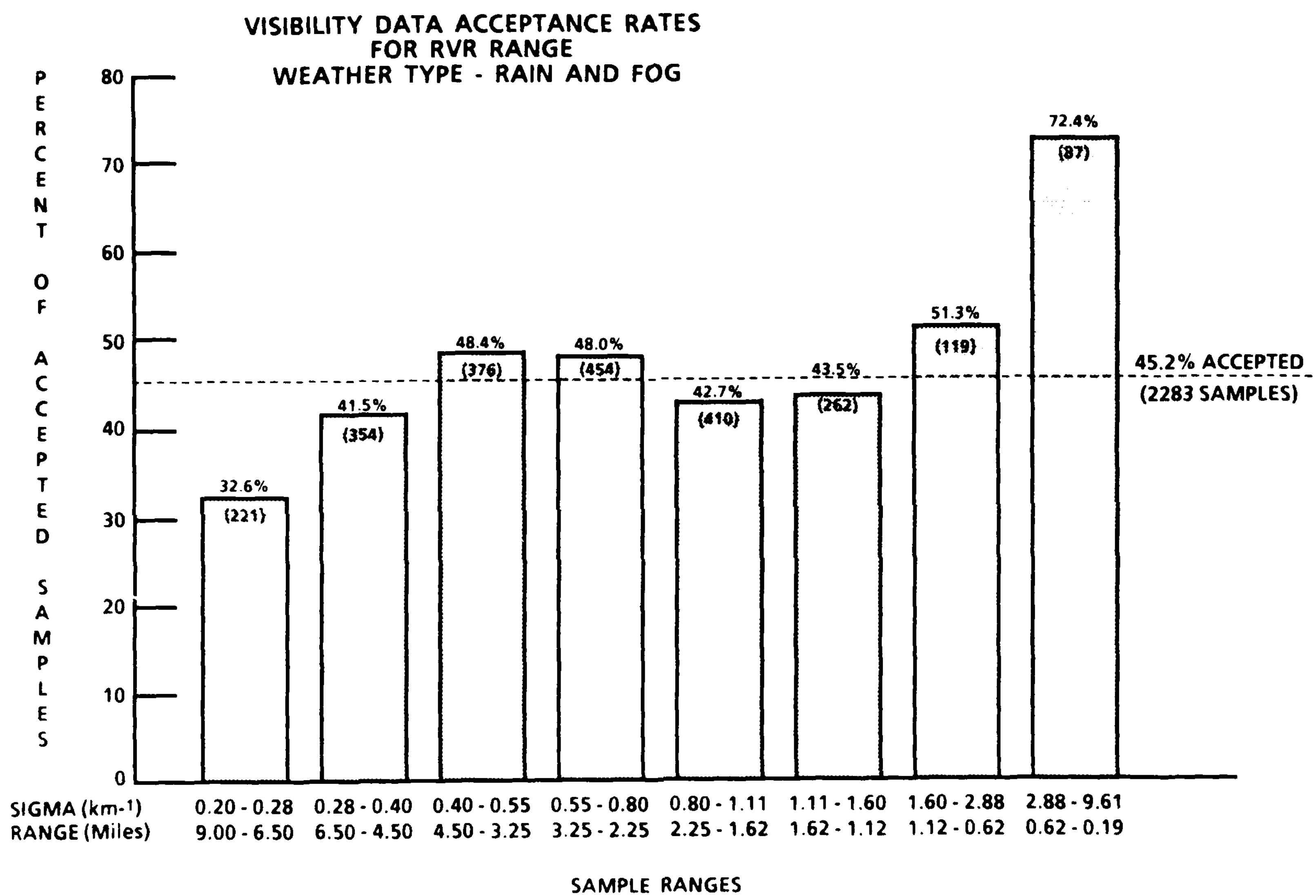


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - RAIN AND FOG) (Cont.)

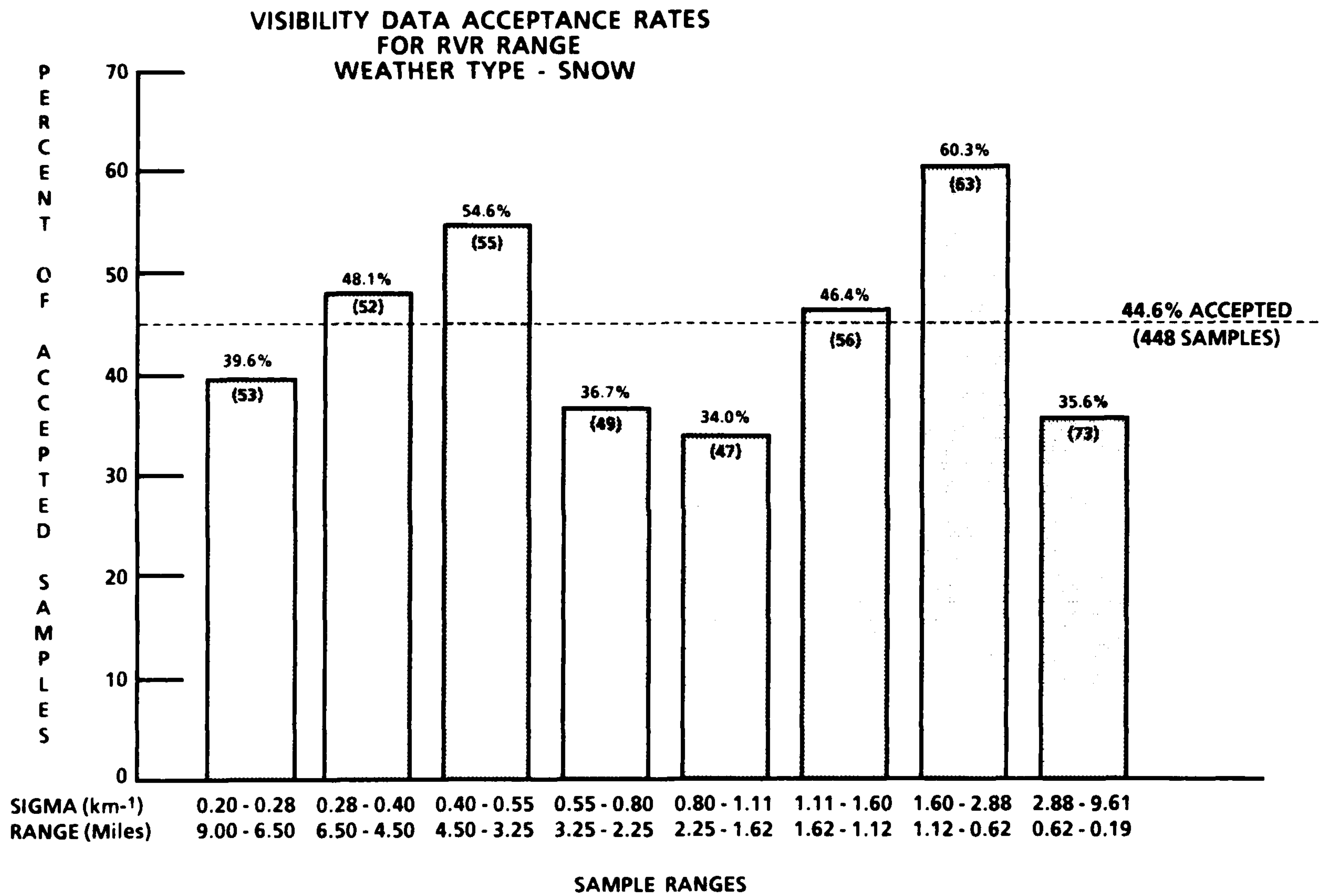


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - SNOW) (Cont.)

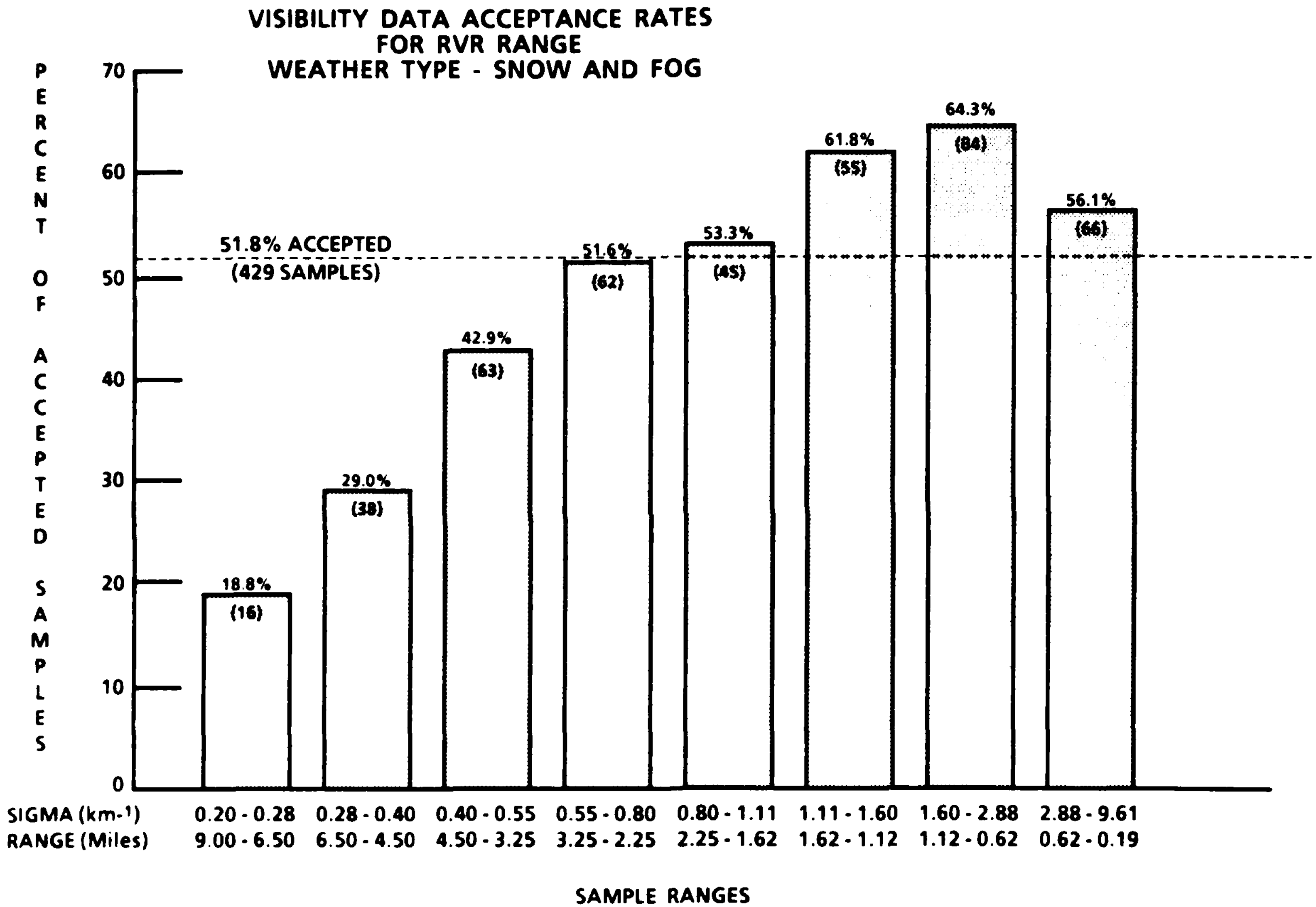


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - SNOW AND FOG) (Cont.)

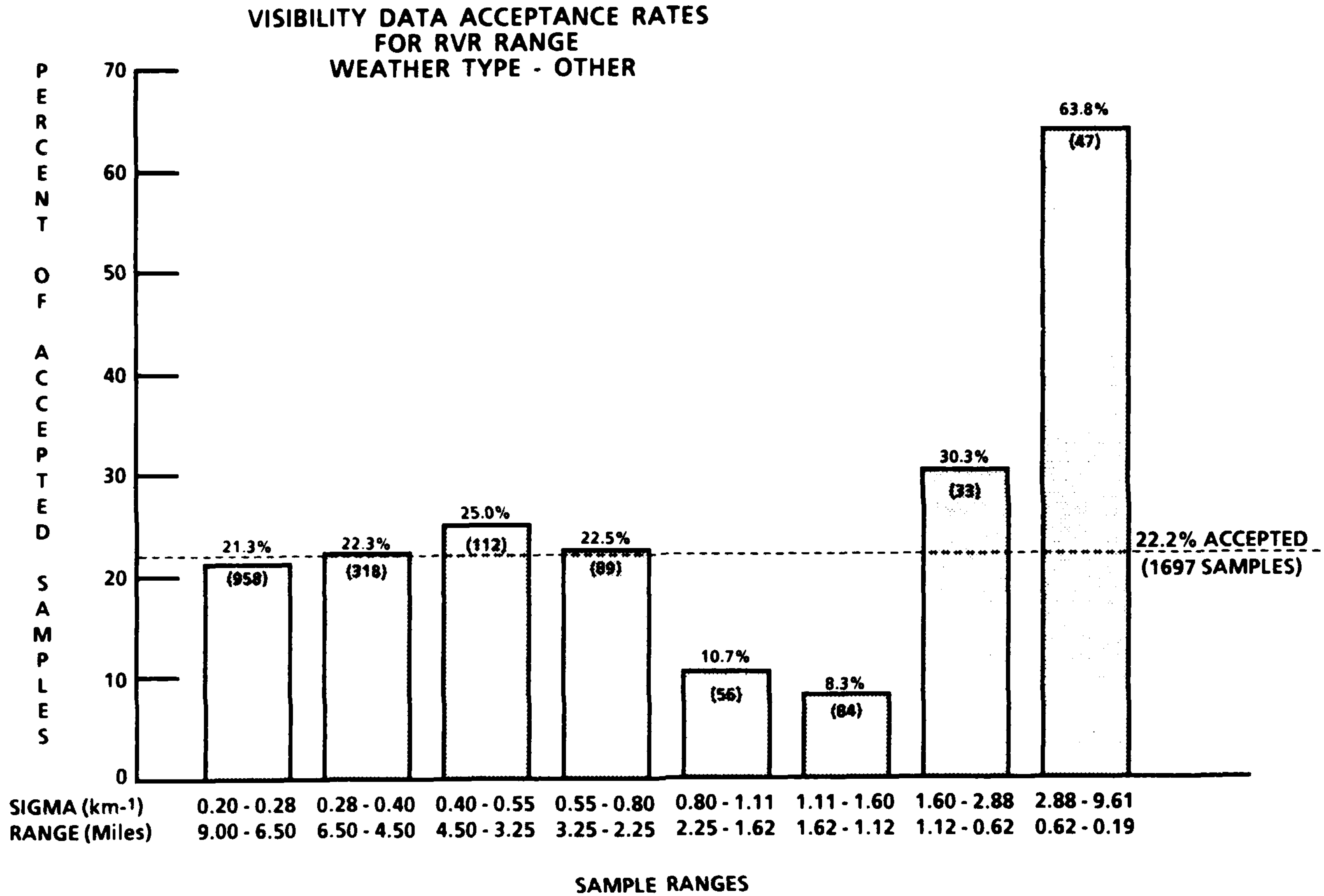


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - OTHER) (Cont.)

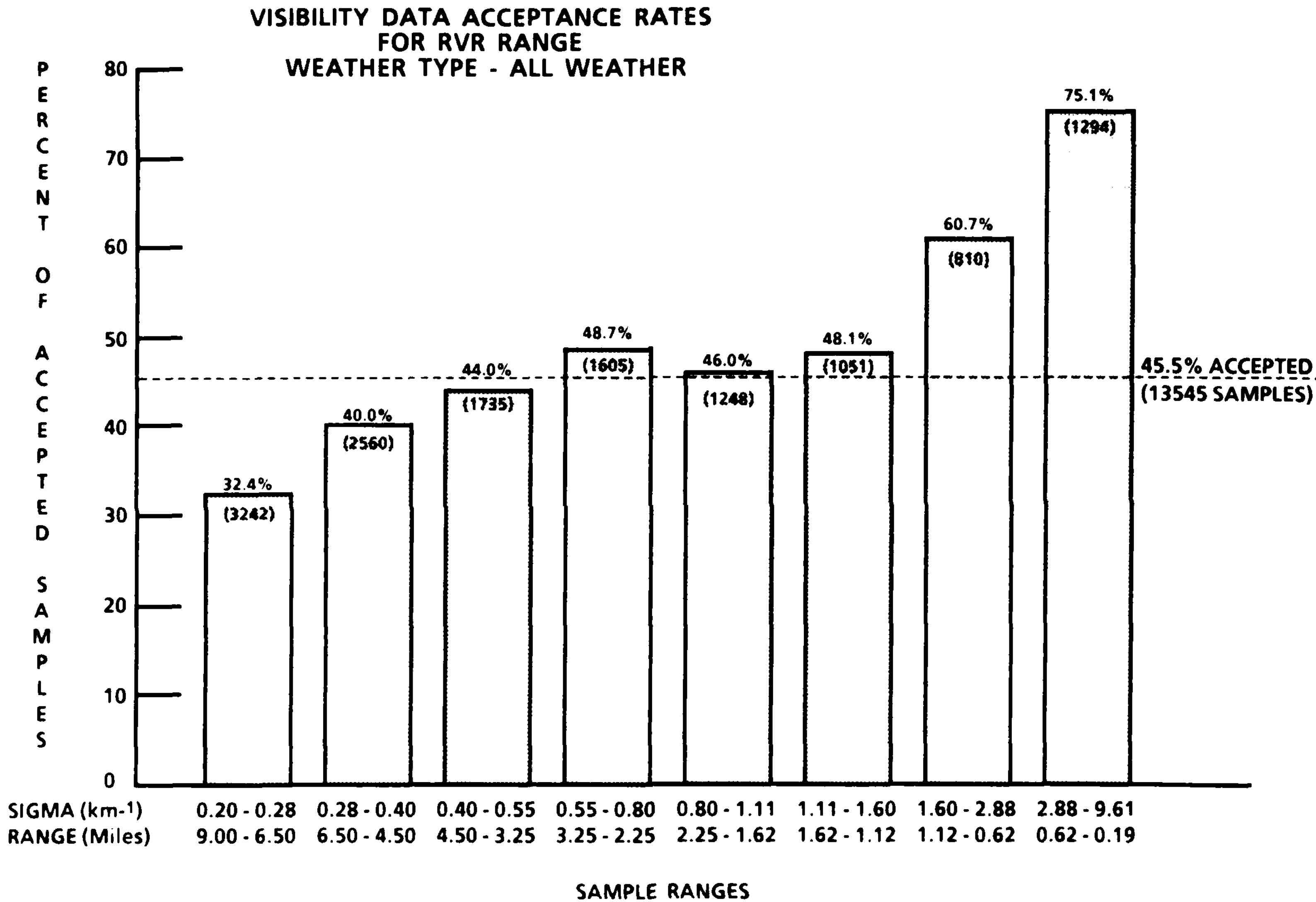


FIGURE 4-6. VISIBILITY DATA ACCEPTANCE RATES FOR AWOS RANGE (WEATHER TYPE - ALL WEATHER) (Cont.)

The detailed program output for each of the 15 four-week time periods contains arrays of sensor data as a function of the sensor tested, ranges of the standard readings, and weather types. The AWOS details are voluminous and are not conducive to further summary. This data will be approached in a different manner in the next analysis (Section 4.6). The RVR details are considered further here.

The RVR detail arrays consist of seven extinction coefficient ranges of the standard and nine groups of ratios of sensor reading to standard (crossed transmissometer, except for the last sigma range) reading, with the number of samples in each of these categories listed. The limits of the ratio ranges for each group number are shown in Table 4-14 and have been previously explained (see Section 3.6). The first step in the summarization of this data was to sum the data for all extinction coefficients. When this was completed, the data set consisted of nine values of the number of samples in each ratio group number, for each weather type, for each time period.

This data was now rearranged and collected by weather type. As in the previous analysis, five of the weather types (ice pellets, rain & ice, rain & snow, snow & ice, and snow grains) have been removed from consideration, since there are not enough cases to be significant. A sample of the results of this consolidation is given in Table 4-15 for the HSS1 and HSS2 sensors under Fog and Haze conditions. The complete set of tables is given in Appendix L. Note that Haze conditions existed during only a few of the time periods. Further, the HSS1 sensor was down during time period 15, when the HSS2 sensor indicated some Haze data. Two additional columns have been included in these tables. The most probable value of group number for any line of data is simply the group number which occurs most frequently. The average group number has been obtained by

TABLE 4-14. DESCRIPTION OF SENSOR AVERAGE GROUP NUMBERS -RVR RANGE-

There are nine groups depending on the ratio of the sensor reading to the crossed transmissometer mean reading.

Group No.	Ratio $\left(\frac{\text{Sensor}}{\text{Xmiss.}}\right)$
1	0 - 0.50
2	0.50 - 0.75
3	0.75 - 0.80
4	0.80 - 0.835
5	0.835 - 1.165
6	1.165 - 1.25
7	1.25 - 1.35
8	1.35 - 2.00
9	>2.00

Relation to Error Limit Tables

Group	Error
5	<16.5%
4 - 6	<25%
3 - 7	<35%
2 - 8	<100%

The number in each Group is obtained form the SENSOR output.

$$Average\ Group\ \# = \frac{\sum_{N=1}^{9} \left| (No.\ in\ Group)_N \times N \right|}{\sum_{N=1}^{9} (No.\ in\ Group)_N}$$

Time Period	Dates		None
1	01/26/84	- 02/23/84	1*
2	02/23/84	- 03/22/84	1
3	03/22/84	- 04/19/84	1
4	04/19/84	- 05/17/84	1
5	05/17/84	- 06/14/84	1
6	06/14/84	- 07/12/84	2**
7	07/12/84	- 08/09/84	2
8	08/09/84	- 09/12/84	2
9	09/12/84	- 10/26/84	2
10	10/26/84	- 11/23/84	2
11	11/23/84	- 12/20/84	2
12	12/20/84	- 01/17/85	2
13	01/17/85	- 02/14/85	2
14	02/14/85	- 03/14/85	2
15	03/14/85	- 04/11/85	2
T	01/26/84	- 04/11/85	

* Normalization #1
Incident of 2/14-2/15/84

** Normalization #2
Incident of 6/26/84

Switched as of 6/22/84

Plot No.	Sensor
1	HSS1
2	HSS2
3	HSSA
4	F15A
5	F15B
6	FG50
7	X-1
8	X-2

TABLE 4-15. COMPARISON OF SENSOR RATIOS - RVR SUMMARY
(Summed over Sigma)

SENSOR: HSS1 WEATHER: FOG

Time Av	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss) 1	2	3	4	5	6	7	8	9	Mst Prb	Av Grp #
1	2554	13	6	11	17	953	221	225	1100	8	8	6 52
2	360	1	9	2	3	129	28	38	148	2	8	6 44
3	756	0	32	6	2	273	130	87	223	3	5	6 16
4	189	0	5	5	5	57	14	67	36	0	7	6 20
5	530	6	90	18	21	320	41	26	8	0	5	4 56
6	1534	1	77	88	97	1119	61	59	32	0	5	4 85
7	2542	0	9	20	33	933	129	350	1067	1	8	6 55
8	1342	0	19	21	15	336	547	308	94	2	6	6 00
9	536	0	1	0	1	397	82	34	21	0	5	5 38
10	1159	50	306	47	36	632	69	12	7	0	5	4 02
11	1611	16	75	46	42	708	303	257	164	0	5	5 55
12	978	3	161	140	124	412	98	30	10	0	5	4 27
13	477	0	1	2	1	108	103	201	61	0	7	6 43
14	[illegible]	0	30	23	22	72	0	0	0	0	5	3 93
T	14715	90	821	429	419	6449	1826	1694	2971	16	5	5 69

SENSOR: HSS2 WEATHER: FOG

Time Av	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss) 1	2	3	4	5	6	7	8	9	Mst Prb	Av Grp #
1	2577	12	89	75	97	1853	315	72	59	5	5	5 04
2	360	0	31	43	28	178	19	31	30	0	5	4 90
3	756	20	72	34	23	491	83	24	8	1	5	4.70
4	189	0	25	6	1	137	17	1	2	0	5	4 67
5	530	9	125	52	81	257	3	3	0	0	5	3 89
6	1534	4	103	98	105	1178	42	4	0	0	5	4 62
7	2536	0	5	46	79	912	240	383	871	0	5	6 35
8	1342	2	12	9	17	408	534	307	50	3	6	5 92
9	536	0	0	2	6	119	148	156	105	0	7	6 43
10	1159	1	70	49	43	665	220	74	37	0	5	5 11
11	1618	213	80	73	92	1007	111	23	19	0	5	4 31
12	978	75	178	63	31	521	84	23	3	0	5	4 13
13	477	23	24	15	9	321	12	13	60	0	5	5 03
14	147	0	0	0	0	123	20	3	1	0	5	5 20
T	14739	359	814	565	612	8170	1848	1117	1245	9	5	5 15

SENSOR: HSS1 WEATHER: HAZE

Time Av	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss) 1	2	3	4	5	6	7	8	9	Mst Prb	Av Grp #
7	5	2	1	0	0	1	0	0	1	0	1	3 40
9	964	0	17	51	93	749	27	11	14	2	5	4 85
11	323	0	0	0	0	265	15	17	26	0	5	5 39
14	78	3	5	2	4	64	0	0	0	0	5	4 55
T	1370	5	23	53	97	1079	42	28	41	2	5	4 95

SENSOR: HSS2 WEATHER: HAZE

Time Av	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss) 1	2	3	4	5	6	7	8	9	Mst Prb	Av Grp #
7	5	2	2	0	0	0	0	1	0	0	1 5	2 60
9	964	0	0	2	1	308	576	53	24	0	6	5 78
11	323	1	0	0	0	130	109	56	27	0	5	5 92
14	78	0	0	0	1	67	2	1	7	0	5	5 31
15	204	0	0	0	0	187	8	7	2	0	5	5 14
T	1574	3	2	2	2	692	695	118	60	0	6	5 69

multiplying the number of samples in each group by the group number, summing, and dividing by the total number of samples. Since the limits on Group 5 are ratios from 0.835 to 1.165, if all of the data lies in this group, then the average group number is 5.00 and all sensor readings are within 16.5 percent of the standard readings. Note, however, that an average group number of 5.00 can also be obtained from 10 samples in Group 1 and 10 samples in Group 9, so that a good average group number does not necessarily signify small sensor errors. This problem is addressed by the next analysis, which would show less than 16.5 percent error for the first case, but greater than 100 percent error for the second example.

A further consolidation can be made if only the overall time period (line T) is considered for each of the sensors and weather conditions. This information is presented as Table 4-16. This allows a direct comparison, for each weather condition, of the total numbers of samples (a reflection of the down time of some of the sensors) and the average group number. For ease of comparison, this data is also presented graphically in Figure 4-7. Note that results for weather conditions of fog, haze, and drizzle & fog show average group numbers close to the "perfect" 5.0. This is due, at least in part, to the fact that sensor normalizations were done during periods of fog. Conditions of drizzle, rain, and rain & fog result in relatively high group numbers, indicating that FSMs are more responsive than the transmissometers, while snow, snow & fog, and other conditions (most of these are high visibility "clear" conditions) are fairly consistently low, indicating that the FSMs are less responsive than the transmissometers. The "All-Weather" chart indicates average group numbers for all of the sensors are between 4 and 6, primarily due to the preponderance of fog conditions in the data sample.

TABLE 4-16. COMPARISON OF SENSOR RATIOS - RVR SUMMARY
(Summed over Sigma and Time)

WEATHER: FOG

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss)									Mst Prb	Av Grp #
		1	2	3	4	5	6	7	8	9		
HSS1	14715	90	821	429	419	6449	1826	1694	2971	16	5	5.69
HSS2	14739	359	874	565	612	8170	1848	1117	1245	9	5	5.15
HSSA	13161	15	758	378	283	7794	1413	1116	1213	191	5	5.36
F15A	7411	891	49	97	117	5809	185	145	117	1	5	4.57
F15B	14648	1953	84	56	42	4436	2269	2228	3192	388	5	5.66
FG50	12391	485	316	294	391	3201	845	528	1286	45	5	5.17
X-1	14732	3	400	369	361	10898	1243	616	836	6	5	5.18
X-2	14790	44	135	116	88	9371	2485	1238	1310	3	5	5.54

WEATHER: HAZE

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss)									Mst Prb	Av Grp #
		1	2	3	4	5	6	7	8	9		
HSS1	1370	5	23	53	97	1079	42	28	41	2	5	4.95
HSS2	1574	3	2	2	2	692	695	118	60	0	6	5.69
HSSA	1292	2	41	65	127	1007	19	23	6	2	5	4.92
F15A	1168	964	0	0	0	176	14	6	8	0	1	1.74
F15B	1525	1	1	0	0	173	98	91	253	908	9	8.06
FG50	1521	21	51	18	7	1342	43	11	27	1	5	4.92
X-1	1574	1	3	5	15	1472	29	22	27	0	5	5.07
X-2	1574	1	1	1	4	1129	314	60	63	1	5	5.39

WEATHER: DRIZZLE

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss)									Mst Prb	Av Grp #
		1	2	3	4	5	6	7	8	9		
HSS1	37	0	0	0	0	0	4	0	28	5	8	7.92
HSS2	37	0	0	0	0	7	7	7	16	0	8	6.86
HSSA	37	0	0	0	0	3	2	1	25	6	8	7.78
F15A	37	0	0	0	0	21	7	6	3	0	5	5.76
F15B	27	27	0	0	0	0	0	0	0	0	1	1.00
FG50	31	0	0	0	0	22	6	3	0	0	5	5.39
X-1	37	0	0	0	0	11	6	5	15	0	8	6.65
X-2	37	0	0	0	0	13	14	9	0	1	6	5.97

WEATHER: DRIZZLE AND FOG

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss)									Mst Prb	Av Grp #
		1	2	3	4	5	6	7	8	9		
HSS1	2180	21	191	43	35	638	152	299	796	5	8	6.09
HSS2	2180	42	309	163	116	1087	199	99	156	9	5	4.71
HSSA	1621	3	259	113	56	839	101	108	139	3	5	4.80
F15A	2074	294	76	113	95	1181	83	90	142	0	5	4.50
F15B	2147	275	42	24	22	1129	151	163	337	4	5	5.10
FG50	1921	2	34	104	177	1233	234	80	55	2	5	5.04
X-1	2182	0	90	159	162	1277	199	201	90	4	5	5.06
X-2	2182	70	30	129	127	1137	238	234	216	1	5	5.28

TABLE 4-16. COMPARISON OF SENSOR RATIOS - RVR SUMMARY
(Summed over Sigma and Time) (Cont.)

WEATHER: RAIN

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss) 1	2	3	4	5	6	7	8	9	Mst Prb	Av Grp #
HSS1	339	1	1	0	0	109	33	15	137	43	8	6.89
HSS2	339	0	0	1	0	117	42	18	125	36	8	6.76
HSSA	339	0	0	0	0	91	36	69	100	43	8	6.91
F15A	182	0	0	0	2	123	12	6	12	27	5	5.91
F15B	339	1	0	1	0	105	16	13	166	37	8	7.01
FG50	321	0	0	0	0	119	31	48	96	27	5	6.63
X-1	340	0	0	0	0	104	51	60	117	8	8	6.63
X-2	340	0	0	0	0	104	46	61	128	1	8	6.64

WEATHER: RAIN AND FOG

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss) 1	2	3	4	5	6	7	8	9	Mst Prb	Av Grp #
HSS1	1527	17	172	22	9	227	62	189	698	131	8	6.59
HSS2	1527	34	175	24	17	567	174	162	268	106	5	5.66
HSSA	1367	0	95	51	47	358	212	155	361	88	8	6.11
F15A	1012	80	22	31	41	734	26	23	37	18	5	4.77
F15B	1525	442	8	6	3	366	129	130	328	113	1	5.01
FG50	1356	14	52	129	88	667	61	46	273	26	5	5.38
X-1	1528	0	5	14	25	1024	133	57	265	5	5	5.65
X-2	1528	8	12	3	3	982	90	128	294	8	5	5.77

WEATHER: SNOW

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss) 1	2	3	4	5	6	7	8	9	Mst Prb	Av Grp #
HSS1	639	11	25	12	11	289	58	58	174	1	5	5.85
HSS2	633	8	150	72	37	186	40	63	78	5	5	4.62
HSSA	187	0	2	0	3	26	5	21	113	17	8	7.38
F15A	572	0	527	32	7	6	0	0	0	0	2	2.11
F15B	452	0	0	3	30	378	34	7	0	0	5	5.03
FG50	223	0	130	29	17	47	0	0	0	0	2	2.92
X-1	639	22	110	111	77	306	7	2	4	0	5	3.91
X-2	538	27	96	105	62	244	1	0	0	3	5	3.78

WEATHER: SNOW AND FOG

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss) 1	2	3	4	5	6	7	8	9	Mst Prb	Av Grp #
HSS1	999	119	16	5	19	613	46	46	134	1	5	4.99
HSS2	999	205	98	49	33	418	83	66	47	0	5	4.11
HSSA	368	196	14	6	5	118	9	9	11	0	1	2.87
F15A	466	18	344	23	31	50	0	0	0	0	2	2.47
F15B	907	40	199	47	32	462	65	44	18	0	5	4.26
FG50	186	39	87	26	11	23	0	0	0	0	2	2.42
X-1	1000	205	85	17	49	613	12	4	14	1	5	3.91
X-2	1000	188	69	10	7	696	22	7	1	0	5	4.05

TABLE 4-16. COMPARISON OF SENSOR RATIOS - RVR SUMMARY
(Summed over Sigma and Time) (Cont.)

WEATHER: OTHER (CLEAR)

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss)									Mst Prb	Av Grp #
		1	2	3	4	5	6	7	8	9		
HSS1	488	13	65	38	29	225	42	36	31	9	5	4.78
HSS2	468	86	141	29	19	174	18	11	5	5	5	3.42
HSSA	486	15	120	38	34	189	17	21	45	7	5	4.37
F15A	373	0	51	12	49	238	9	5	9	0	5	4.52
F15B	374	1	17	8	3	276	29	16	19	5	5	5.17
FG50	393	27	190	58	43	61	3	1	5	5	2	2.97
X-1	404	3	24	23	12	299	12	8	21	2	5	4.89
X-2	404	5	6	11	21	317	13	8	19	4	5	5.05

WEATHER: ALL WEATHER

Sensor	Tot No	No in Group # (Ratio Sensor/Crossed Xmiss)									Mst Prb	Av Grp #
		1	2	3	4	5	6	7	8	9		
HSS1	22294	277	1314	602	619	9629	2265	2365	5010	213	5	5.72
HSS2	22522	737	1689	905	836	11418	3106	1661	2000	170	5	5.11
HSSA	18858	231	1289	651	555	10425	1814	1523	2013	357	5	5.30
F15A	13235	2247	1069	308	342	8338	336	278	271	46	5	4.15
F15B	22021	2737	350	147	134	7372	2803	2699	4324	1455	5	5.66
FG50	18343	588	860	658	734	11715	1223	717	1742	106	5	5.07
X-1	22436	234	717	698	701	16004	1692	975	1389	26	5	5.12
X-2	22393	342	350	376	310	13973	3242	1746	2033	21	5	5.42

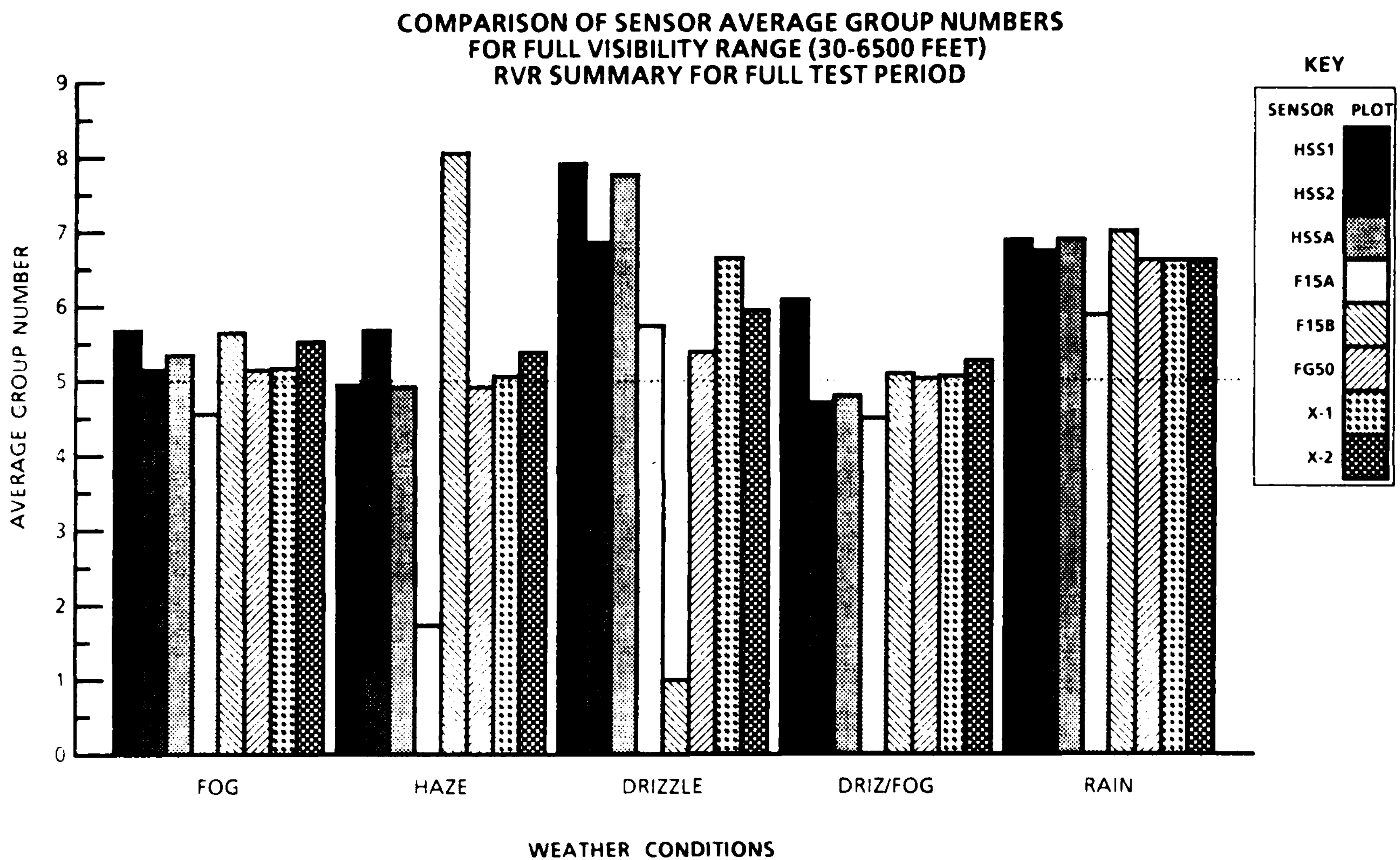


FIGURE 4-7. SENSOR RATIO AVERAGE GROUP NUMBERS FOR RVR RANGE

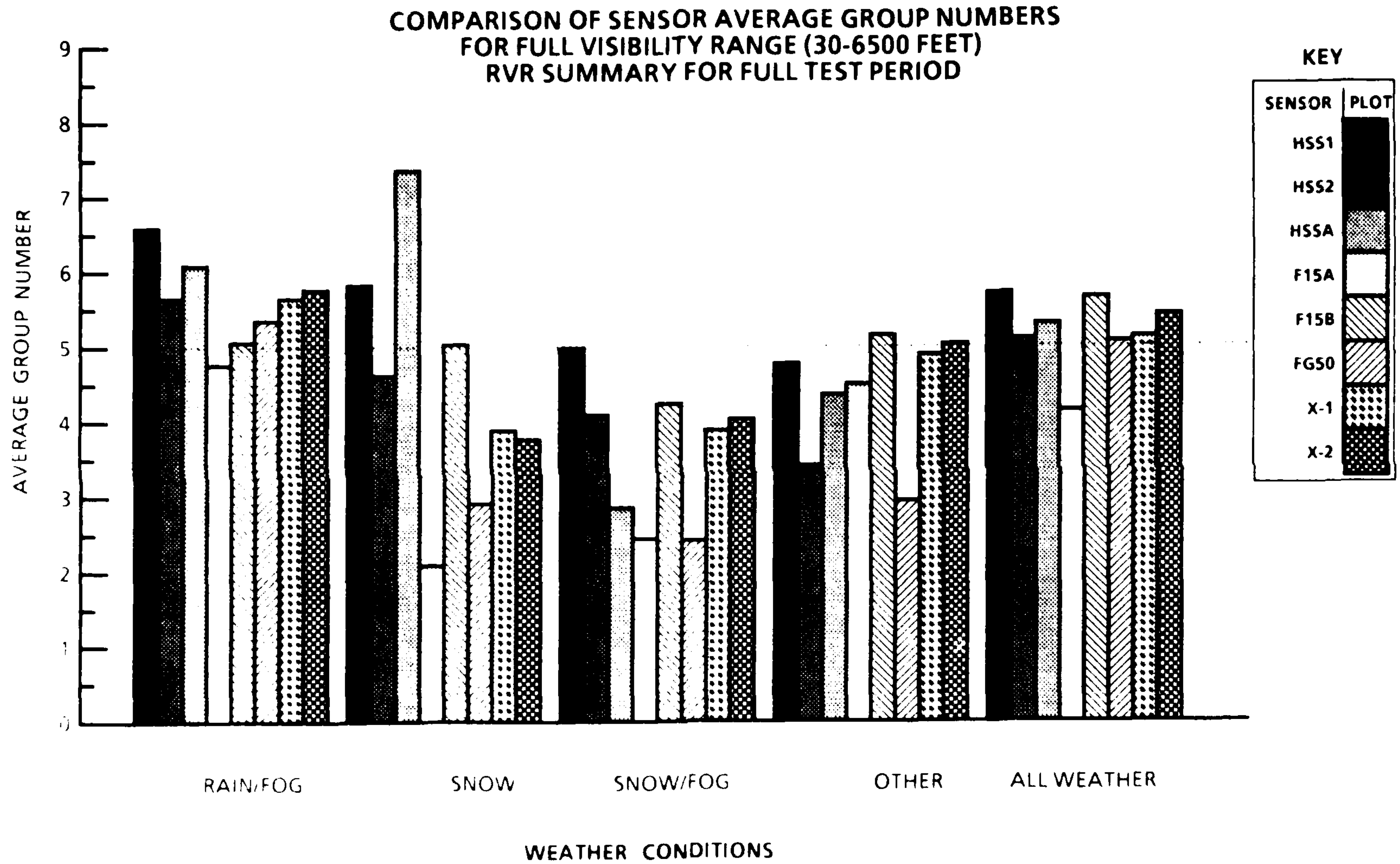


FIGURE 4-7. SENSOR RATIO AVERAGE GROUP NUMBERS FOR RVR RANGE (Cont.)

4.6 Sensor Data Comparisons

As a final output, the SENSOR program provides cumulative summaries of the comparisons of each of the sensors with the standard (as defined in the previous section) transmissometer reading, both for the RVR and AWOS ranges. The RVR tables are related to the previous analysis, as the error groups used are the same. The previous analysis looked at the number in each group and allowed determination of whether a sensor was reading consistently higher or lower than the standard. In this analysis, the absolute value of the error is considered, so that equal numbers of high and low readings are not balanced out to make the sensor seem more accurate than it is. The tables indicate an error E greater than 16.5 percent, 25 percent, 35 percent, and 2X. As explained previously (see Section 3.6) these four groups are actually $-16.5\% < E < +16.5\%$; $-20\% < E < +25\%$; $-25\% < E < +35\%$; and $-100\% < E < +100\%$.

The data from the final cumulative summary for the HSS1 sensor (for time period 15) containing error groups as a function of sigma range for each sensor compared to the standard transmissometer readings has been summarized in Table 4-17. The complete set of eight tables is given in Appendix M. Only the ten significant weather conditions used in the previous analyses have been included. The final four columns in each table convert the error groups from number with error greater than the limit to percent with error less than the limit. As an example, sensor HSS1 shows that a total (overall sigma range) of 5639 out of 13406 samples lie within 25 percent of the standard reading. This translates to:

$$\frac{13406-5639}{13406} \times 100 = 57.9\%$$

of the sensor readings with an error of less than 25 percent of the standard readings.

TABLE 4-17. COMPARISON OF HSS1 SENSOR WITH AVERAGE OF TRANSMISSOMETER READINGS
(RVR Summary for Full Test Period)

RANGES 1: 1.5-4.0 Km⁻¹ (6500-2500 ft) 2: 4.0-11.0 Km⁻¹ (2500-900 ft) 3: 11.0-38.0 Km⁻¹ (900-250 ft) T: 1.5-38.0 Km⁻¹ (6500-250 ft)

Weather Type	Range	Tot No	No With Error >				% Within Error of			
			16.5%	25%	35%	100%	16.5%	25%	35%	100%
FOG	1	3715	2724	2241	1617	21	26.7	39.7	56.5	99.4
	2	4698	2851	2009	1201	34	39.3	57.2	74.4	99.3
	3	4993	2145	1389	874	40	57.0	72.2	82.5	99.2
	T	13406	7720	5639	3692	95	42.4	57.9	72.5	99.3
HAZE	1	157	77	62	47	5	51.0	60.5	70.1	96.8
	2	453	84	37	11	2	81.5	91.8	97.6	99.6
	3	677	127	53	13	0	81.2	92.2	98.1	100.0
	T	1287	288	152	71	7	77.6	88.2	94.5	99.5
DRIZZLE	1	24	24	21	21	5	0.0	12.5	12.5	79.2
	2	13	13	12	12	0	0.0	7.7	7.7	100.0
	3	0	0	0	0	0				
	T	37	37	33	33	5	0.0	10.8	10.8	86.5
DRIZZLE AND FOG	1	1151	1064	967	739	17	7.6	16.0	35.8	98.5
	2	771	432	355	252	9	44.0	54.0	67.3	98.8
	3	258	46	33	22	0	52.2	87.2	91.5	100.0
	T	2180	1542	1355	1013	26	29.3	37.8	53.5	98.8
RAIN	1	244	205	172	157	44	16.0	29.5	35.7	82.0
	2	51	25	25	25	0	51.0	51.0	51.0	100.0
	3	44	0	0	0	0	100.0	100.0	100.0	100.0
	T	339	230	197	182	44	32.2	41.9	46.3	87.0

Weather Type	Range	Tot No	No With Error >				% Within Error of			
			16.5%	25%	35%	100%	16.5%	25%	35%	100%
RAIN AND FOG	1	793	720	684	623	147	9.2	13.8	21.4	81.5
	2	436	360	337	273	1	17.4	22.7	37.4	99.8
	3	298	220	208	122	0	26.2	30.2	59.1	100.0
	T	1527	1300	1229	1018	148	14.9	19.5	33.3	90.3
SNOW	1	520	289	232	180	12	44.4	55.4	65.4	97.7
	2	119	61	49	31	0	48.7	58.8	74.0	100.0
	3	0	0	0	0	0				
	T	639	350	281	211	12	45.2	56.0	67.0	98.1
SNOW AND FOG	1	687	154	102	63	2	77.6	85.2	90.8	99.7
	2	198	122	109	97	20	38.4	45.0	51.0	89.9
	3	111	107	107	107	95	3.6	3.6	3.6	14.4
	T	996	383	318	267	117	61.6	68.1	73.2	88.3
OTHER	1	116	83	72	47	19	28.5	37.9	59.5	83.6
	2	199	107	74	42	3	46.2	62.8	78.9	98.5
	3	172	73	46	29	0	57.6	73.3	83.1	100.0
	T	487	263	172	118	22	46.0	60.6	75.8	95.5
ALL WEATHER	1	7407	5340	4553	3494	272	27.9	38.5	52.8	96.3
	2	6938	4055	3007	1944	69	41.6	56.7	72.0	99.0
	3	6553	2718	1836	1167	135	58.5	72.0	82.2	97.9
	T	20898	12113	9396	6605	476	42.0	55.0	68.4	97.7

For ease in comparison, the percentages for the total RVR range of extinction coefficients (1.5-38 km^{-1} or 6500-250 feet visibility) have been extracted from the eight tables and rearranged to present data for all eight sensors under each weather condition. This information is presented in Tables 4-18. Note that the final "all-weather" table provides convenient overall figures-of-merit for the sensors. However, these should be used with care, as this analysis does not cover all phases of the comparison.

To help visualize the information on these tables, a series of bar charts has been used to present the data graphically. The meaning of the bars and the percentages involved has been explained further on Figure 4-8. The data comparison presented in Figures 4-9 shows the effect of weather conditions and extinction coefficient group for each sensor, and correspond directly to the information in Table 4-17. The final composite data from Table 4-18 is presented in Figure 4-10.

A similar analysis is done by SENSOR for the AWOS range. Here the errors are expressed in terms of reporting increments (RI), as is standard custom, rather than in percentages. The reporting increments are described in Section 3.6. Just as for the RVR range, Table 4-19 summarizes the data for the HSS1 sensor for AWOS from the final cumulative summary showing error groups as a function of sigma range for each sensor compared to the standard (1000-foot baseline) transmissometer readings. The complete set of eight tables is given in Appendix N. These are also shown graphically in Figures 4-11. Finally, the percentages for the total AWOS range of extinction coefficients of 0.2-9.6 km $^{-1}$ (9.0-0.19 miles visibility) have been extracted and combined into Table 4-20, which presents data for all eight sensors under each of the ten weather conditions studied. Figure 4-12 is a graphical presentation of the information in these tables. Refer to Figure 4-8 for an explanation of the symbols used on the bar charts.

TABLE 4-18. COMPARISON OF SENSORS WITH AVERAGE OF TRANSMISSOMETER READINGS FOR FULL VISIBILITY RANGE (250-6500 FEET)
(RVR Summary for Full Test Period)

WEATHER: FOG

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	13406	42.4	57.9	72.5	99.3
HSS2	13406	54.5	71.8	83.5	98.7
HSSA	11804	57.3	70.7	82.7	98.3
F15A	6894	78.7	83.0	86.4	88.8
F15B	13283	27.9	44.0	60.5	85.1
FG50	11280	65.4	75.8	82.5	95.5
X-1	13367	[illegible]	87.2	92.9	99.9
X-2	13425	[illegible]	79.6	89.4	99.7

WEATHER: DRIZZLE

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	37	0.0	10.8	10.8	86.5
HSS2	37	18.9	37.8	56.8	100.0
HSSA	37	8.1	13.5	16.2	83.8
F15A	37	56.8	75.7	91.9	100.0
F15B	37	0.0	0.0	0.0	0.0
FG50	31	71.0	90.3	100.0	100.0
X-1	37	29.7	46.0	59.5	100.0
X-2	37	35.1	73.0	97.3	97.3

WEATHER: RAIN

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	339	32.2	41.9	46.3	87.0
HSS2	339	34.5	46.9	52.5	89.4
HSSA	339	26.8	37.5	57.8	87.3
F15A	182	67.6	75.3	78.6	85.2
F15B	339	31.0	35.7	39.8	88.8
FG50	321	37.1	46.7	61.7	91.6
X-1	340	30.6	45.6	63.2	97.7
X-2	340	30.6	44.1	62.1	99.7

WEATHER: HAZE

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	1287	77.6	88.2	94.5	99.5
HSS2	1491	[illegible]	87.6	95.6	99.8
HSSA	1209	[illegible]	88.7	95.8	99.7
F15A	1106	15.9	17.2	17.7	18.4
F15B	1490	10.2	16.8	22.9	39.5
FG50	1438	91.4	94.7	96.0	98.5
X-1	1491	94.0	96.2	97.9	99.9
X-2	1491	70.4	91.6	95.6	99.9

WEATHER: DRIZZLE AND FOG

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	2180	29.3	37.8	53.5	98.8
HSS2	2180	49.9	64.3	76.3	97.7
HSSA	1621	51.8	61.4	75.1	99.6
F15A	2014	58.6	67.5	77.4	85.4
F15B	2147	52.6	60.6	69.4	87.0
FG50	1921	64.2	85.6	95.2	99.8
X-1	2182	58.5	75.1	91.6	99.8
X-2	2182	52.1	68.8	85.5	96.8

WEATHER: RAIN AND FOG

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	1527	14.9	19.5	33.3	90.3
HSS2	1527	37.1	49.6	61.8	90.8
HSSA	1367	26.2	45.1	60.2	93.6
F15A	1012	72.5	79.2	84.5	90.3
F15B	1525	24.1	33.0	42.2	64.5
FG50	1356	49.2	60.2	73.1	97.1
X-1	1528	67.0	77.4	82.0	99.7
X-2	1528	63.3	70.4	78.7	99.0

TABLE 4-18. COMPARISON OF SENSORS WITH AVERAGE OF TRANSMISSOMETER READINGS FOR FULL VISIBILITY RANGE (250-6500 FEET) (RVR Summary for Full Test Period) (Cont.)

WEATHER: SNOW

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	639	45.2	56.0	67.0	98.1
HSS2	639	29.1	41.2	62.3	98.0
HSSA	187	13.9	18.2	29.4	90.9
F15A	572	1.1	2.3	7.9	100.0
F15B	452	83.6	97.8	100.0	100.0
FG50	223	21.1	28.7	41.7	100.0
X-1	639	47.9	61.0	78.7	96.6
X-2	538	45.4	57.1	76.6	94.4

WEATHER: OTHER

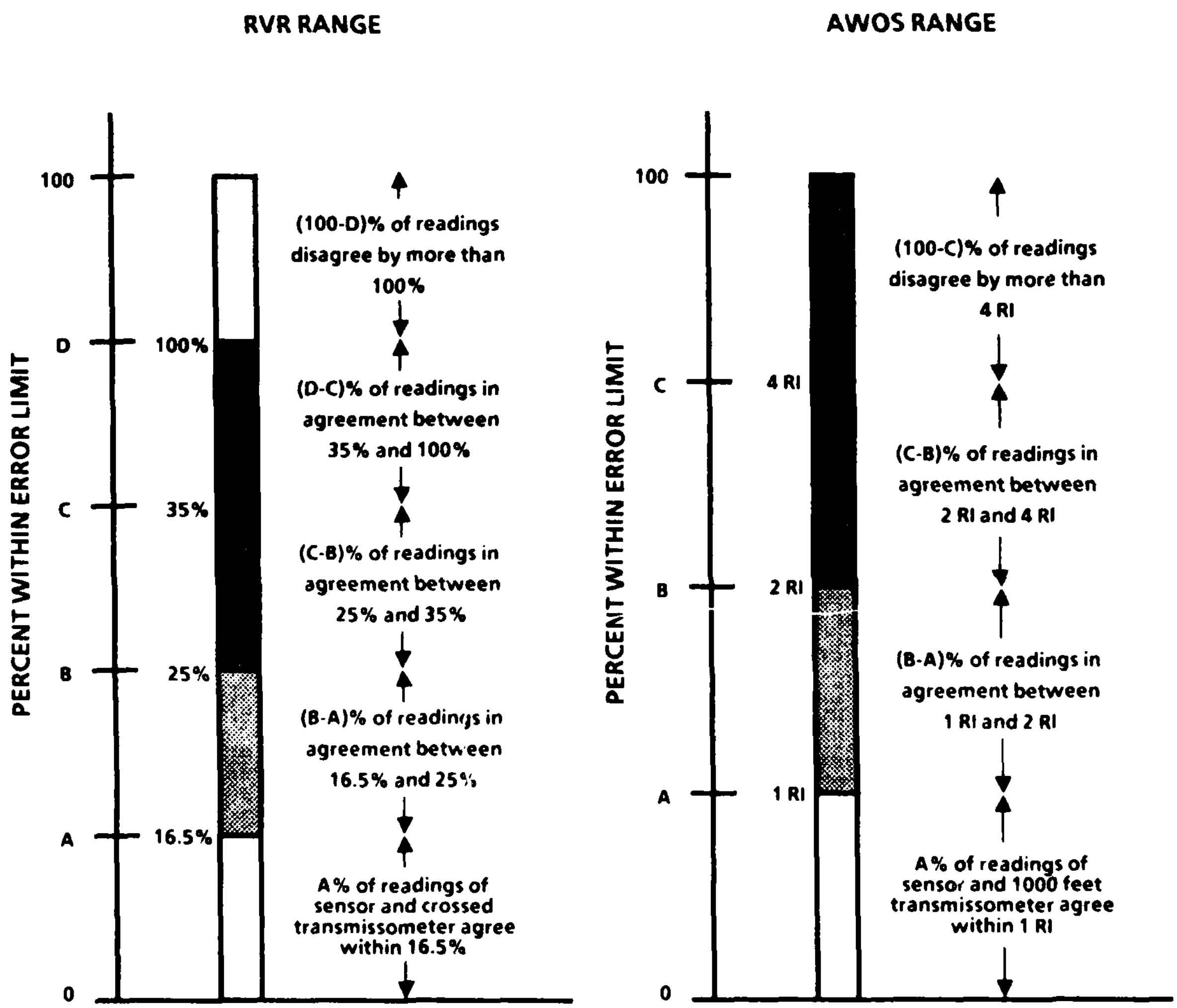
Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	487	46.0	60.6	75.8	95.5
HSS2	487	35.5	43.1	51.3	81.3
HSSA	485	38.8	49.3	61.4	95.5
F15A	373	63.8	79.4	83.9	100.0
F15B	440	73.0	82.5	88.9	98.6
FG50	393	15.5	27.2	42.2	91.9
X-1	403	74.0	79.9	87.6	98.8
X-2	403	77.2	86.1	92.1	98.3

WEATHER: SNOW AND FOG

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	996	61.6	68.1	73.2	88.3
HSS2	996	42.0	53.6	65.2	79.7
HSSA	366	32.2	36.1	40.2	47.0
F15A	463	10.8	17.5	22.5	96.3
F15B	907	50.9	61.6	71.7	95.6
FG50	186	12.4	18.3	32.3	79.0
X-1	997	61.5	67.6	69.7	79.6
X-2	997	69.8	72.7	74.4	81.4

WEATHER: ALL WEATHER

Sensor	Tot No	% Within Error of			
		16.5%	25%	35%	100%
HSS1	20898	42.0	55.0	68.4	97.7
HSS2	21102	49.7	67.6	79.3	96.6
HSSA	17415	53.5	66.4	78.5	96.6
F15A	12653	62.9	68.2	72.8	83.3
F15B	20620	32.1	45.5	58.9	81.5
FG50	17149	63.3	74.4	82.0	96.1
X-1	20984	72.4	83.2	90.2	98.8
X-2	20941	61.4	77.3	87.3	98.3



NOTES:
1) Any portion of the column may be missing, depending on the data
2) The column is totally blank when all readings agree within the lowest limit (16.5% or 1 RI)
3) NONE indicates no reading in that column.

FIGURE 4-8. DESCRIPTION OF SENSOR COMPARISON CHARTS

COMPARISON OF HSS1 SENSOR WITH AVERAGE OF TRANSMISSOMETOR READINGS RVR SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

KEY

PLOT	SIGMA Km^{-1} (Visibility Feet)
1	1.5 - 4.0 (6500 - 2500)
2	4.0 - 11.0 (2500 - 900)
3	11.0 - 38.0 (900 - 250)
T	1.5 - 38.0 (6500 - 250)

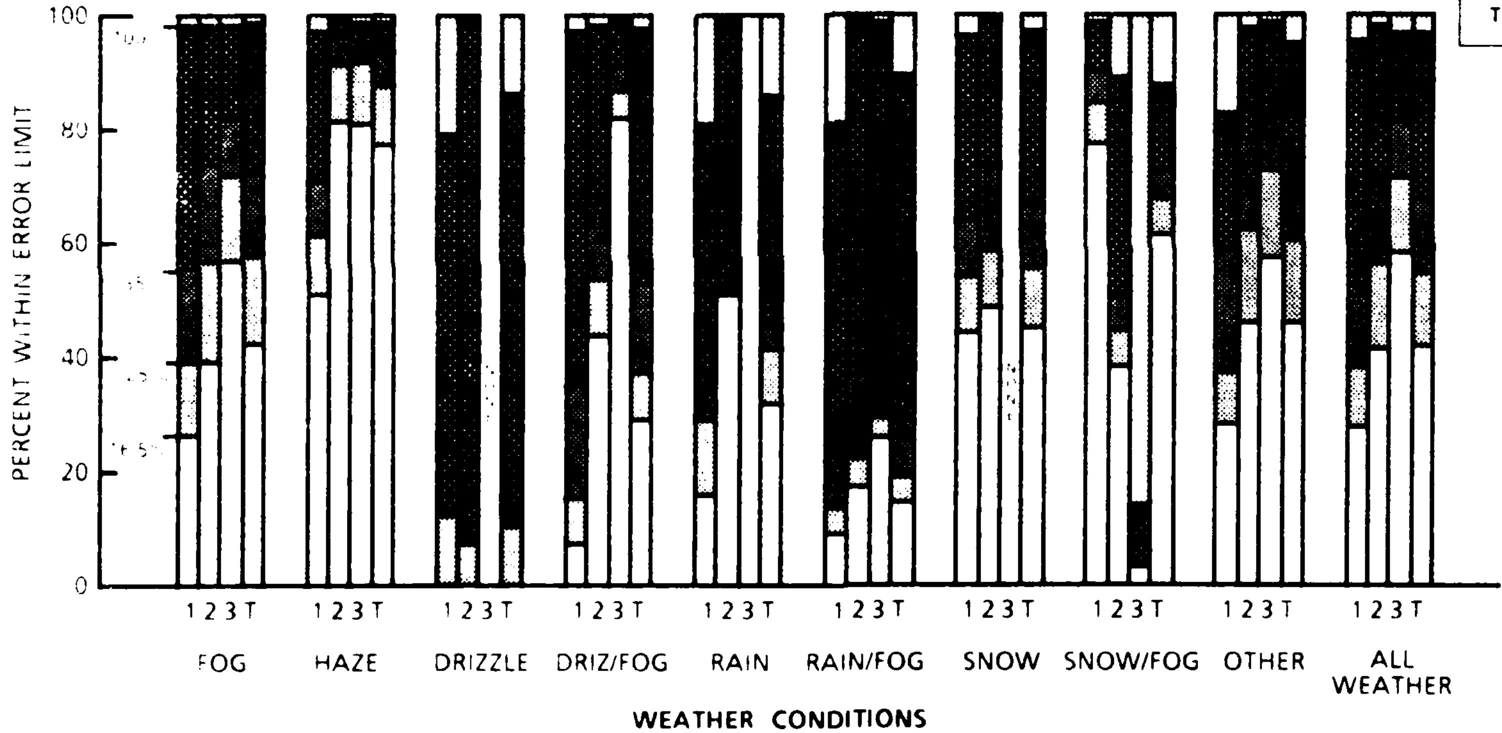
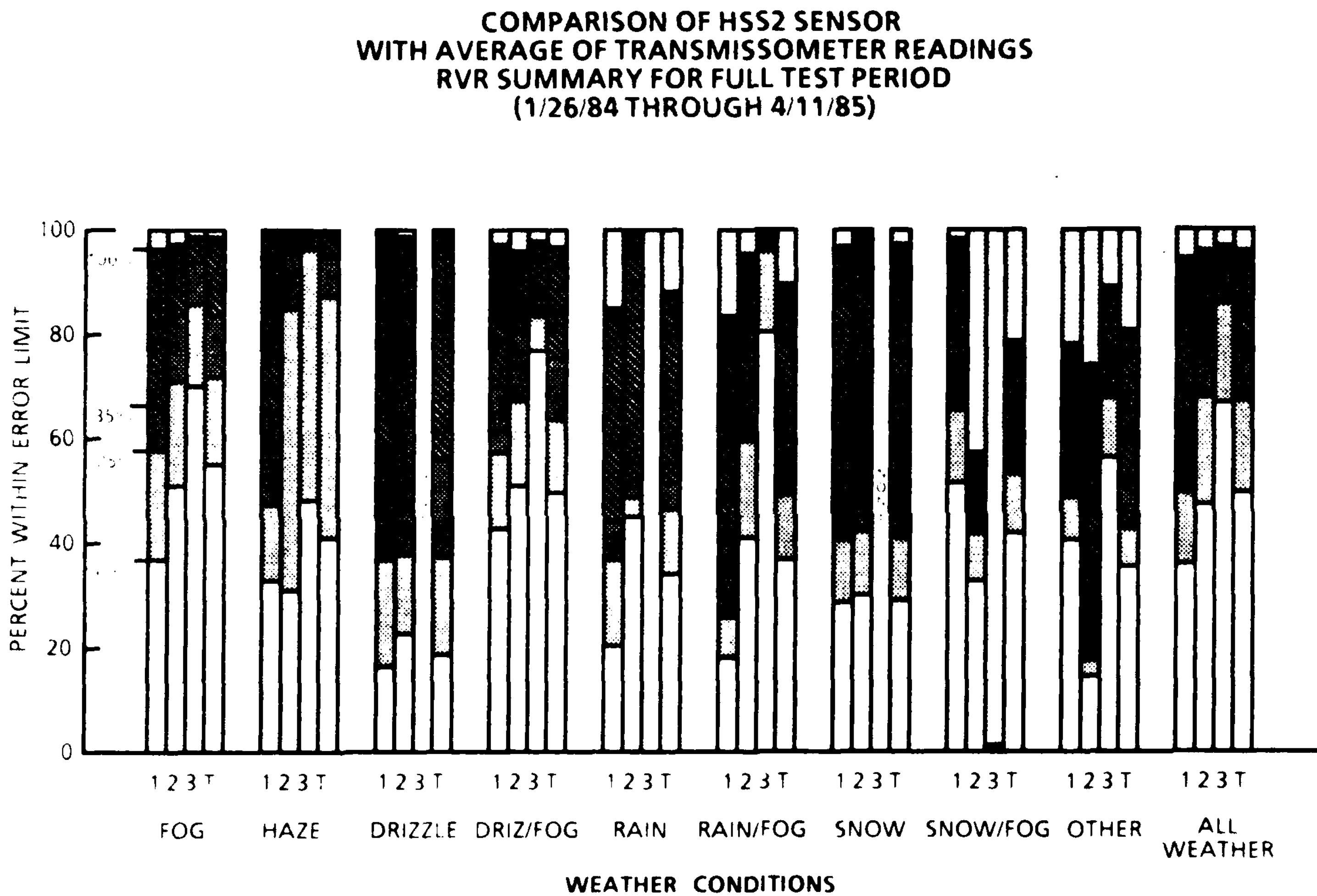


FIGURE 4-9. ERROR RANGE ANALYSIS FOR RVR RANGE



KEY

PLOT	SIGMA Km[1] (Visibility Feet)
1	1.5 - 4.0 (6500 - 2500)
2	4.0 - 11.0 (2500 - 900)
3	11.0 - 38.0 (900 - 250)
T	1.5 - 38.0 (6500 - 250)

FIGURE 4-9. ERROR RANGE ANALYSIS FOR RVR RANGE (Cont.)

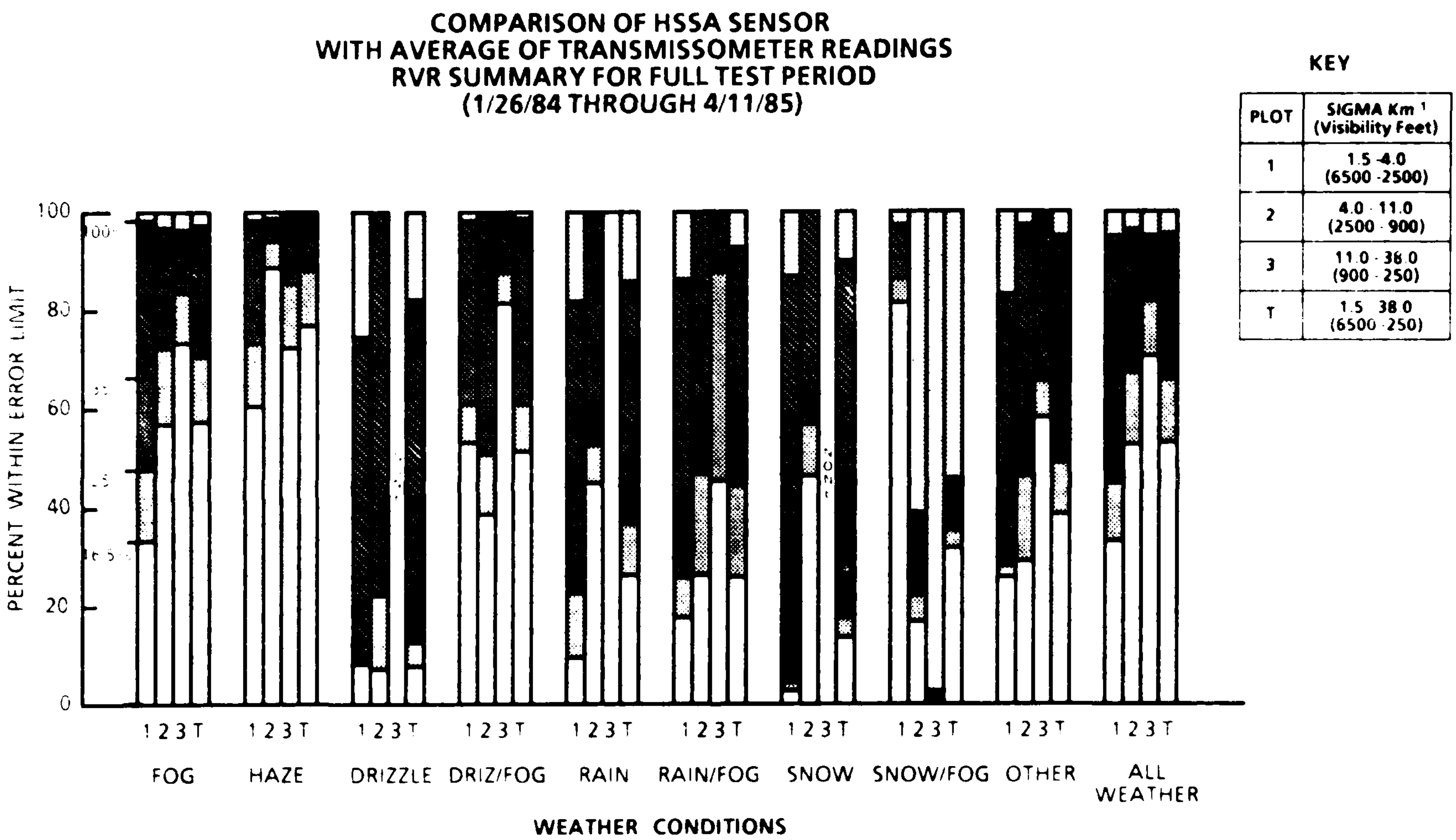
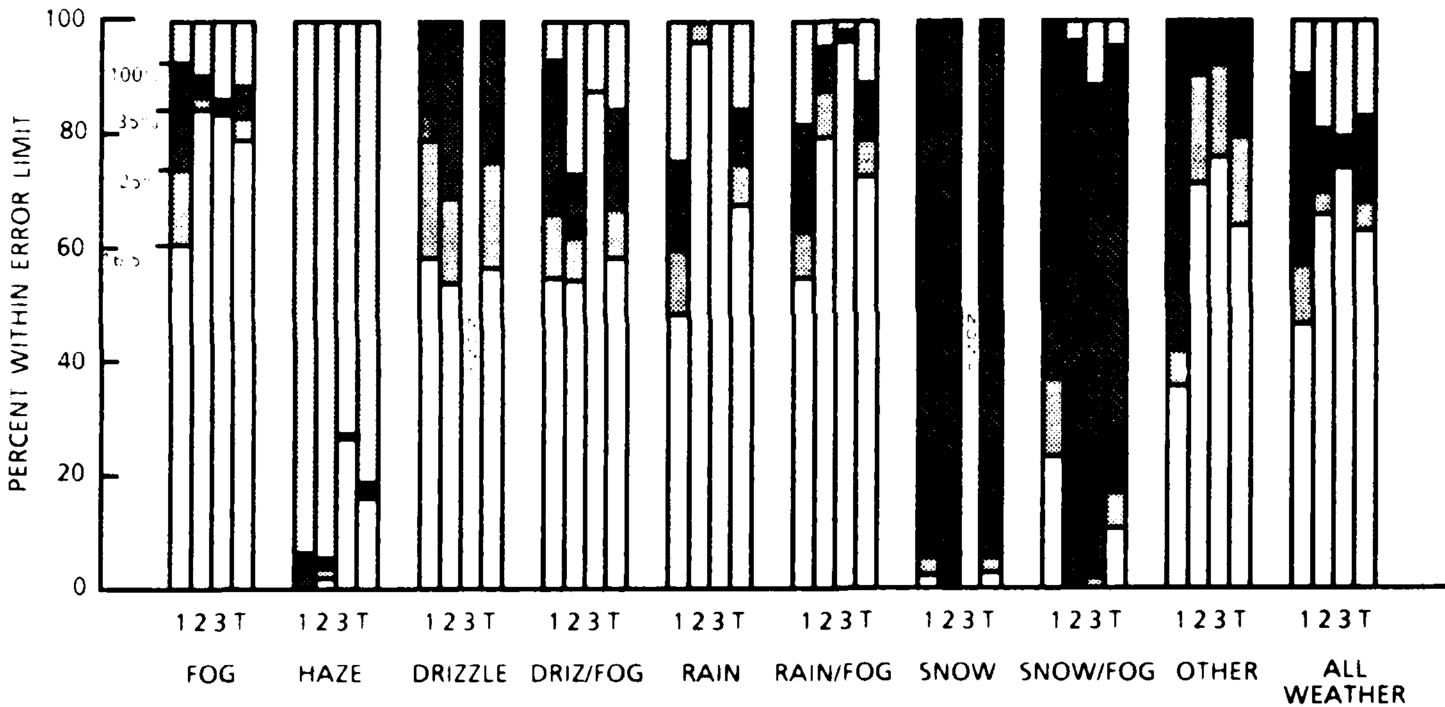


FIGURE 4-9. ERROR RANGE ANALYSIS FOR RVR RANGE (Cont.)

COMPARISON OF FI5A SENSOR WITH AVERAGE OF TRANSMISSOMETER READINGS RVR SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

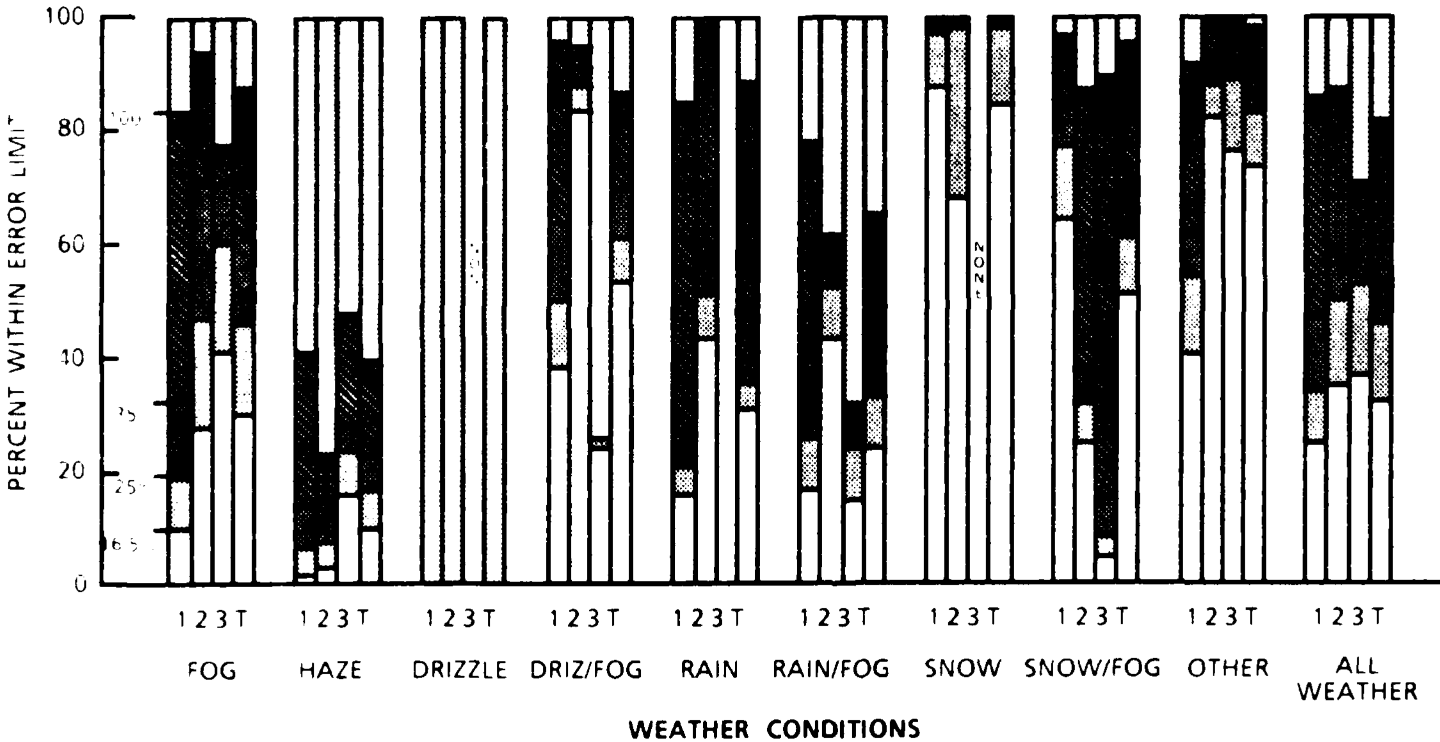


KEY

PLOT	SIGMA Km⁻¹ (Visibility Feet)
1	1.5 - 4.0 (6500 - 2500)
2	4.0 - 11.0 (2500 - 900)
3	11.0 - 38.0 (900 - 250)
T	1.5 - 38.0 (6500 - 250)

FIGURE 4-9. ERROR RANGE ANALYSIS FOR RVR RANGE (Cont.)

COMPARISON OF FI5B SENSOR WITH AVERAGE OF TRANSMISSOMETER READINGS RVR SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

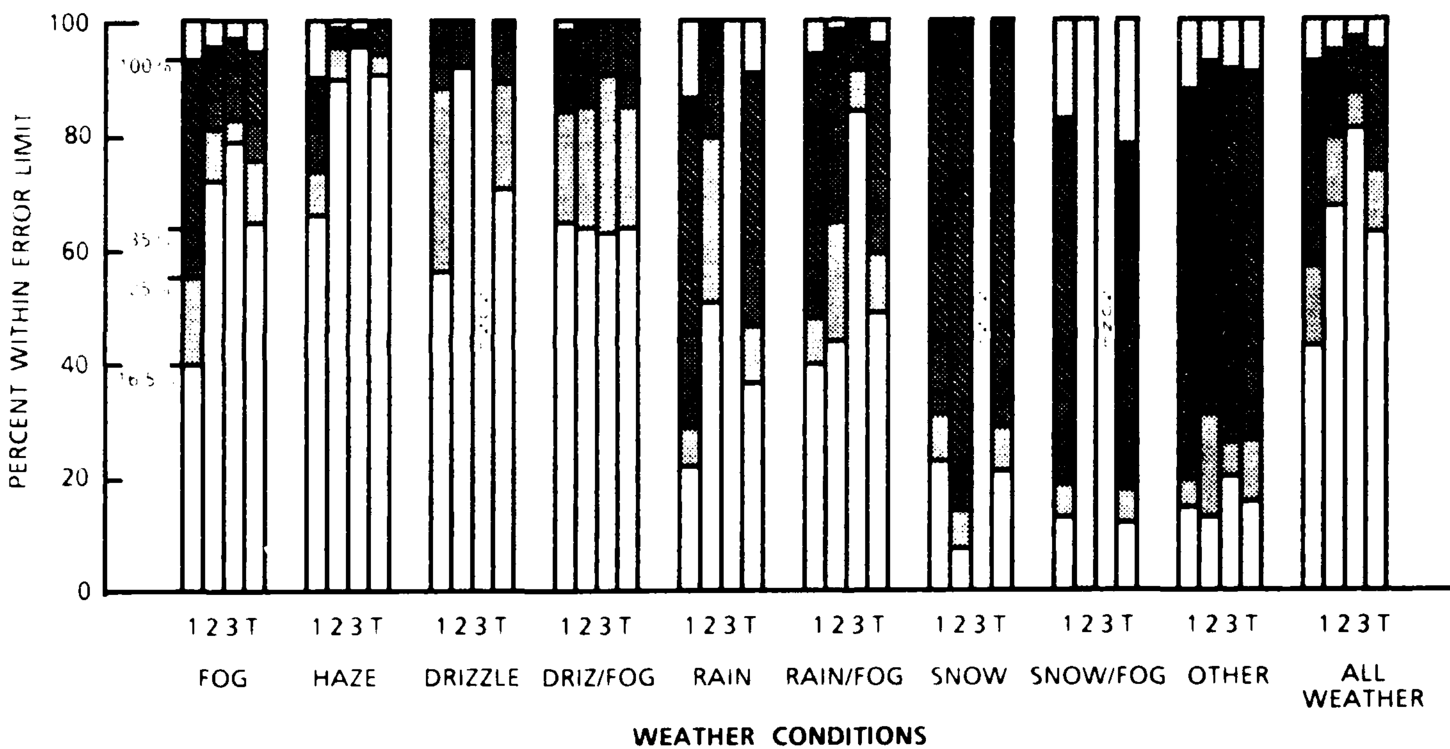


KEY

PLOT	SIGMA Km⁻¹ (Visibility Feet)
1	1.5 -4.0 (6500 -2500)
2	4.0 - 11.0 (2500 - 900)
3	11.0 - 38.0 (900 - 250)
T	1.5 - 38.0 (6500 -250)

FIGURE 4-9. ERROR RANGE ANALYSIS FOR RVR RANGE (Cont.)

COMPARISON OF FG50 SENSOR WITH AVERAGE OF TRANSMISSOMETER READINGS RVR SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

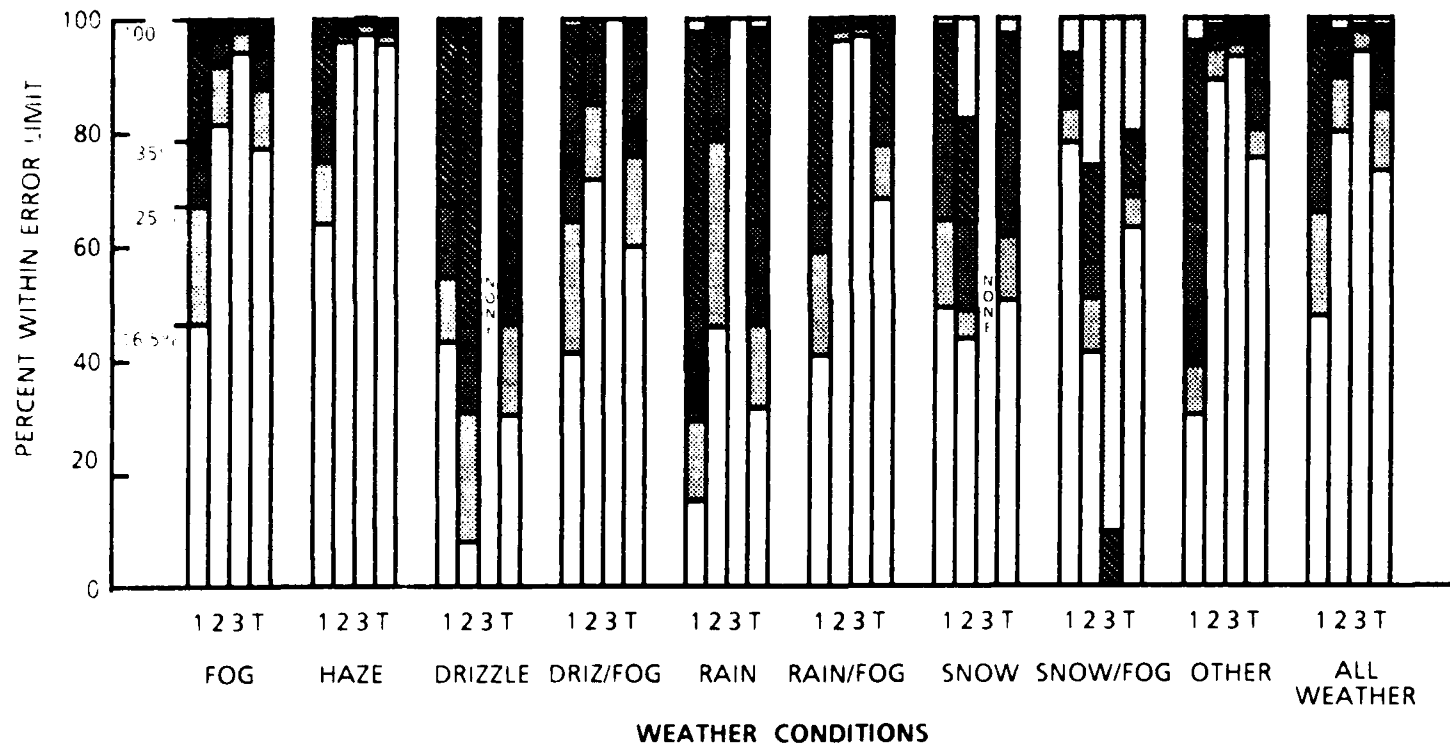


KEY

PLOT	SIGMA Km^{-1} (Visibility Feet)
1	1.5 - 4.0 (6500 - 2500)
2	4.0 - 11.0 (2500 - 900)
3	11.0 - 38.0 (900 - 250)
T	1.5 - 38.0 (6500 - 250)

FIGURE 4-9. ERROR RANGE ANALYSIS FOR RVR RANGE (Cont.)

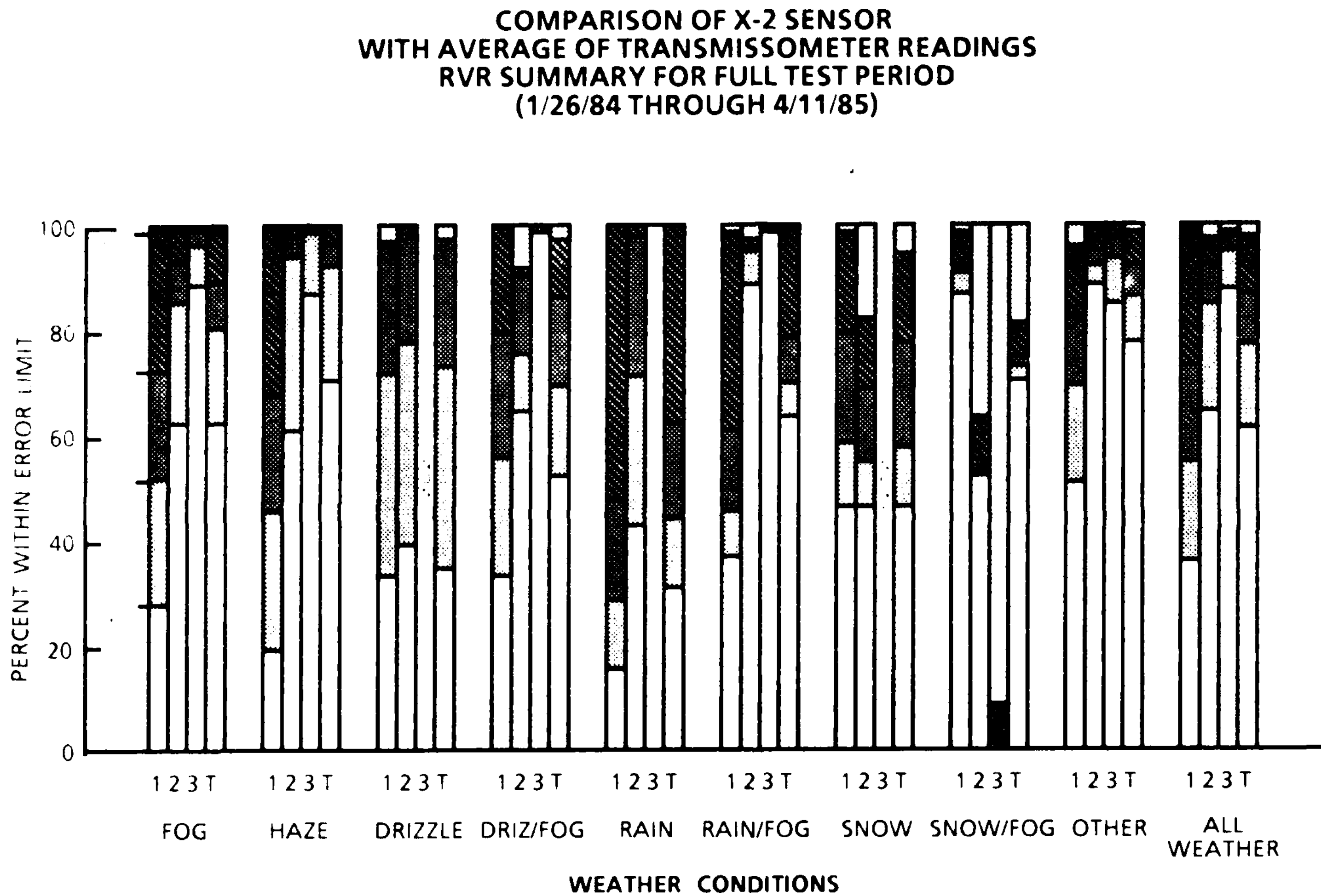
COMPARISON OF X-1 SENSOR WITH AVERAGE OF TRANSMISSOMETER READINGS RVR SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)



KEY

PLOT	SIGMA Km^{-1} (Visibility Feet)
1	1.5 - 4.0 (6500 - 2500)
2	4.0 - 11.0 (2500 - 900)
3	11.0 - 38.0 (900 - 250)
T	1.5 - 38.0 (6500 - 250)

FIGURE 4-9. ERROR RANGE ANALYSIS FOR RVR RANGE (Cont.)

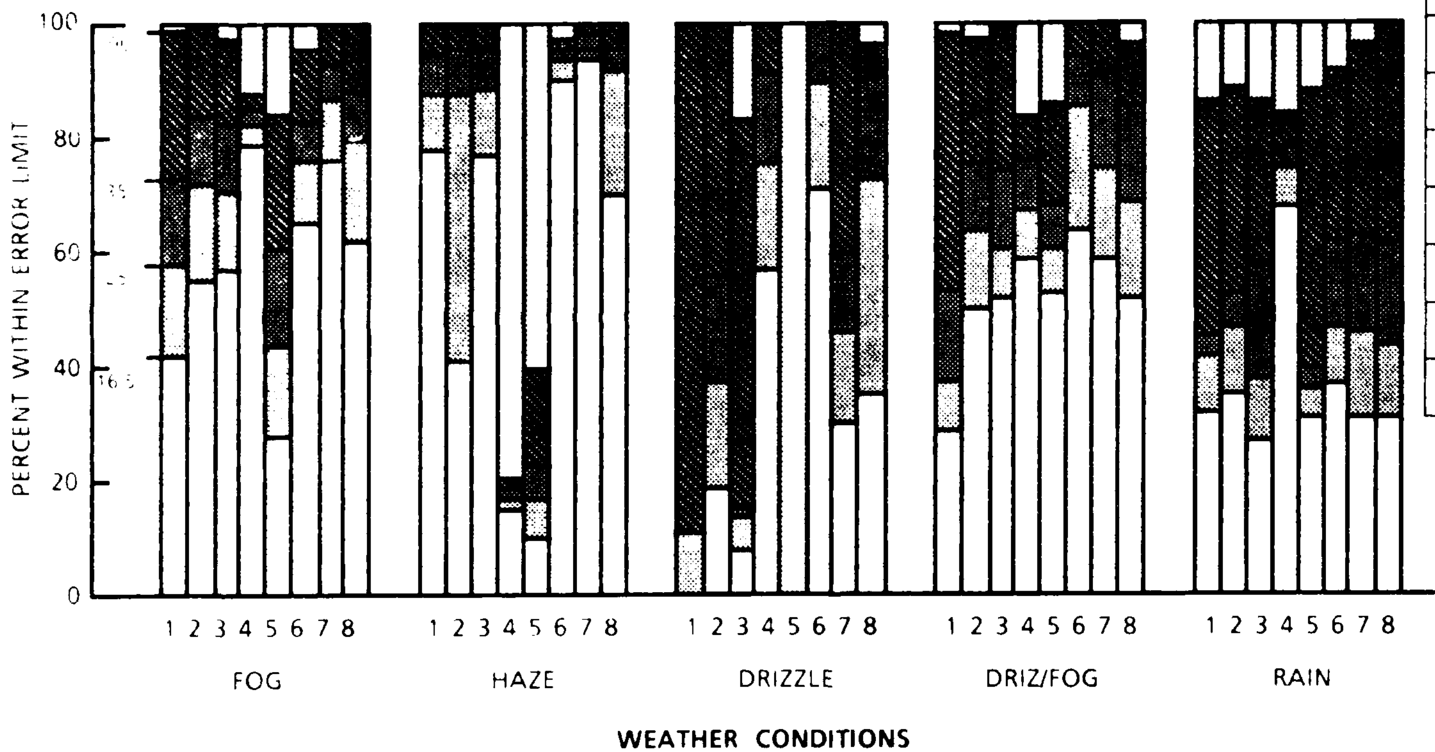


KEY

PLOT	SIGMA Km^{-1} (Visibility Feet)
1	1.5 - 4.3 (6500 - 2500)
2	4.0 - 11.0 (2500 - 900)
3	11.0 - 38.0 (900 - 250)
T	1.5 - 38.0 (6500 - 250)

FIGURE 4-9. ERROR RANGE ANALYSIS FOR RVR RANGE (Cont.)

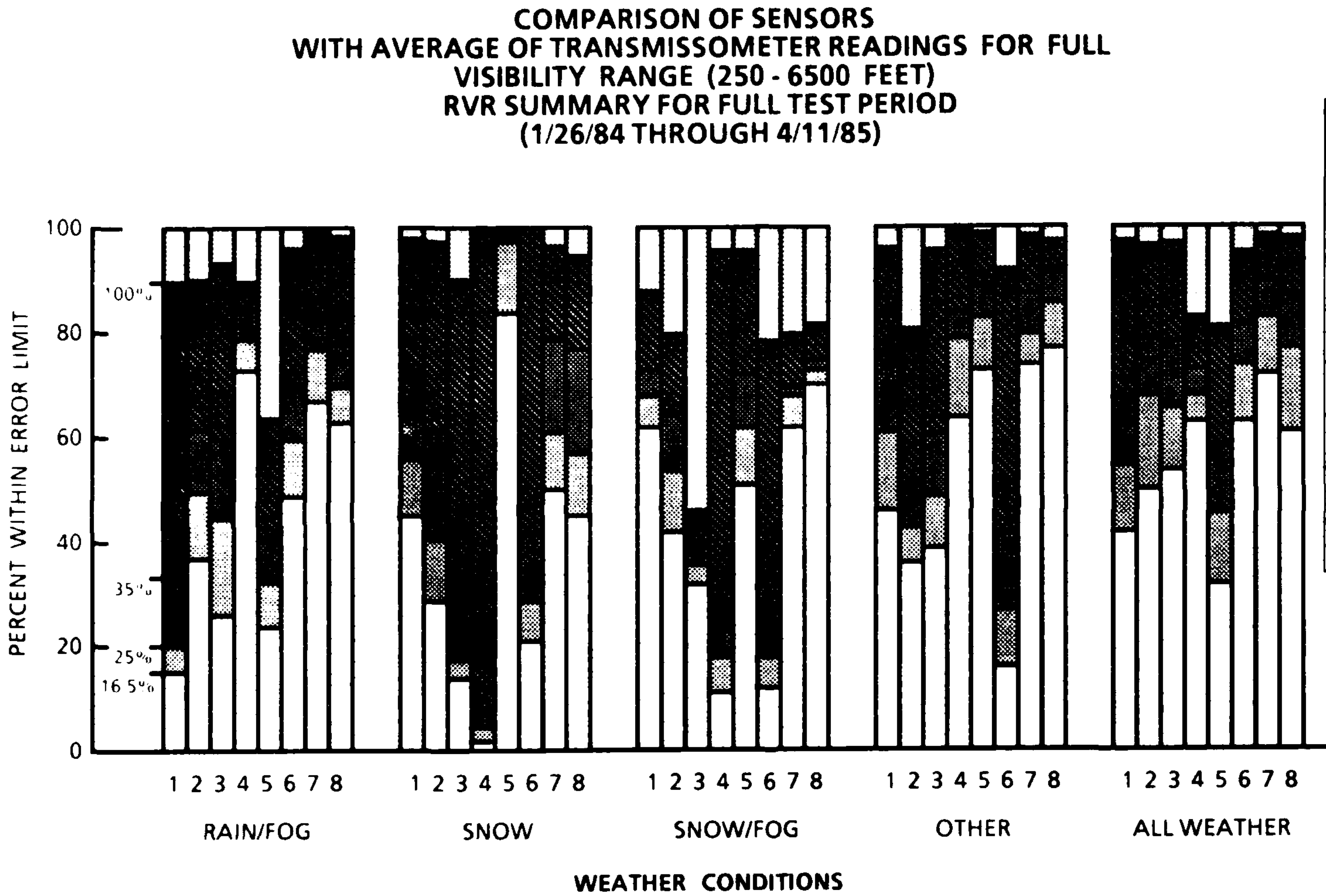
COMPARISON OF SENSORS WITH AVERAGE OF TRANSMISSOMETER READINGS FOR FULL VISIBILITY RANGE (250 - 6500 FEET) RVR SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)



KEY

PLOT	SENSOR
1	HSS1
2	HSS2
3	HSSA
4	F15A
5	F15B
6	FG50
7	X-1
8	X-2

FIGURE 4-10. ERROR RANGE ANALYSIS SUMMED OVER SIGMA, FOR RVR RANGE



KEY

PLOT	SENSOR
1	HSS1
2	HSS2
3	HSSA
4	F15A
5	F15B
6	FG50
7	X-1
8	X-2

FIGURE 4-10. ERROR RANGE ANALYSIS SUMMED OVER SIGMA, FOR RVR RANGE (Cont.)

TABLE 4-19. COMPARISON OF HSS1 SENSOR WITH 1000-FOOT TRANSMISSOMETER READINGS
(AWOS *Summary for Full Test Period*)

RANGES 1: 0.20 - 0.33 km (9.00 - 5.50 mi) 2: 0.33 - 0.66 km (5.50 - 2.75 mi) 3: 0.66 - 1.60 km (2.75 - 1.125 mi)
4: 1.60 - 9.61 km (1.125 - 0.187 mi) T: 0.20 - 9.61 Km (9.00 - 0.187 mi)

Weather Type	Range	Tot No	No With Error >			% Within Error of		
			1 R.I.	2 R.I.	4 R.I.	1 R.I.	2 R.I.	4 R.I.
FOG	1	527	341	238	40	35.3	54.8	92.4
	2	562	427	257	15	24.0	54.3	97.3
	3	493	346	151	2	29.8	69.4	99.6
	4	865	37	1	0	95.7	99.9	100.0
	T	2447	1151	647	57	53.0	73.6	97.7
HAZE	1	336	252	157	42	25.0	53.3	87.5
	2	331	216	139	15	34.7	58.0	95.5
	3	85	54	27	1	36.5	68.2	98.8
	4	50	1	0	0	98.0	100.0	100.0
	T	802	523	323	58	34.8	59.7	92.8
DRIZZLE	1	21	13	11	1	38.1	47.6	95.2
	2	6	6	5	2	0.0	16.7	66.7
	3	10	9	9	0	10.0	10.0	100.0
	4	2	0	0	0	100.0	100.0	100.0
	T	39	28	25	3	28.2	35.9	92.3
DRIZZLE AND FOG	1	57	45	36	9	21.1	36.8	84.2
	2	145	119	80	9	17.9	44.8	93.8
	3	268	218	97	1	18.7	63.8	99.7
	4	197	25	1	0	87.3	99.5	100.0
	T	667	407	214	19	39.0	67.9	97.2
RAIN	1	143	59	24	10	58.7	76.2	93.0
	2	100	87	62	19	13.0	38.0	81.0
	3	57	51	37	14	10.5	35.1	75.4
	4	29	6	3	0	79.3	89.7	100.0
	T	329	203	136	43	38.3	58.7	86.9
RAIN AND FOG	1	122	95	79	42	22.1	35.3	65.6
	2	380	304	226	81	20.0	40.5	78.7
	3	385	331	223	39	14.0	42.1	89.9
	4	124	27	7	0	78.2	94.4	100.0
	T	1011	757	535	162	25.1	47.1	84.0
SNOW	1	27	9	4	0	66.7	85.2	100.0
	2	56	22	8	2	60.7	85.7	96.4
	3	51	15	8	0	70.6	84.3	100.0
	4	64	5	0	0	92.2	100.0	100.0
	T	198	51	20	2	74.2	89.9	99.0
SNOW AND FOG	1	6	5	4	1	16.7	33.3	83.3
	2	53	31	19	14	41.5	64.2	73.6
	3	72	15	10	2	79.2	86.1	97.2
	4	91	3	2	1	96.7	97.8	98.9
	T	222	54	35	18	75.7	84.2	91.9
OTHER	1	257	140	107	21	45.5	58.4	91.8
	2	55	46	36	6	16.4	34.6	89.1
	3	20	13	9	2	35.0	55.0	90.0
	4	39	3	0	0	92.3	100.0	100.0
	T	371	202	152	29	45.6	59.0	92.2
ALL WEATHER	1	1498	960	671	166	35.9	55.2	88.9
	2	1688	1258	832	163	25.5	50.7	90.3
	3	1441	1052	571	61	27.0	60.4	95.8
	4	1461	107	14	1	92.7	99.0	99.9
	T	6088	3377	2088	391	44.5	65.7	93.6

TABLE 4-20. COMPARISON OF SENSORS WITH 1000-FOOT TRANSMISSOMETER READINGS FOR FULL VISIBILITY RANGE (0.2-9.0 miles) (AWOS Summary for Full Test Period)

WEATHER: SNOW

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	198	74.2	89.9	99.0
HSS2	200	67.0	88.0	100.0
HSSA	45	57.8	80.0	100.0
F15A	160	50.0	78.1	99.4
F15B	165	50.3	64.9	95.8
FG50	91	63.7	86.8	91.2
X-1	200	81.5	97.0	99.0
X-2	183	80.3	92.9	98.4

WEATHER: OTHER

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	371	45.6	59.0	92.2
HSS2	372	60.8	85.2	97.3
HSSA	324	37.0	63.6	94.1
F15A	214	72.0	86.5	94.4
F15B	349	18.9	35.2	69.9
FG50	292	73.3	91.8	98.6
X-1	352	46.3	67.1	93.2
X-2	349	45.3	66.5	92.6

WEATHER: SNOW AND FOG

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	222	75.7	84.2	91.9
HSS2	222	57.7	76.6	94.6
HSSA	73	38.4	48.0	67.1
F15A	99	65.7	90.9	99.0
F15B	197	72.1	90.4	98.5
FG50	89	33.7	67.4	94.4
X-1	222	73.9	80.2	84.7
X-2	222	77.0	89.2	92.8

WEATHER: ALL WEATHER

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	6088	44.5	65.7	93.6
HSS2	6150	59.5	80.9	96.3
HSSA	5071	41.2	65.7	95.4
F15A	3775	58.6	76.8	89.6
F15B	5824	31.5	45.4	77.9
FG50	4999	60.1	82.0	96.2
X-1	6066	55.7	76.5	96.1
X-2	6127	51.6	75.0	98.0

TABLE 4-20. COMPARISON OF SENSORS WITH 1000-FOOT TRANSMISSOMETER READINGS FOR FULL VISIBILITY RANGE (0.2-9.0 miles) (AWOS Summary for Full Test Period) (Cont.)

WEATHER: FOG

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	2447	53.0	73.6	97.7
HSS2	2470	66.7	85.8	98.3
HSSA	2113	50.9	[illegible]	98.3
F15A	1165	60.8	78.4	90.6
F15B	2372	34.4	45.8	78.5
FG50	2160	59.9	80.7	96.5
X-1	2406	56.7	75.4	97.2
X-2	2481	51.6	72.4	98.2

WEATHER: DRIZZLE

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	39	28.2	35.9	92.3
HSS2	38	42.1	76.3	92.1
HSSA	39	25.6	35.9	92.3
F15A	35	51.4	97.1	100.0
F15B	35	20.0	40.0	51.4
FG50	36	50.0	61.1	97.2
X-1	45	33.3	57.8	88.9
X-2	45	24.4	60.0	91.1

WEATHER: RAIN

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	329	38.3	58.7	86.9
HSS2	330	43.0	64.9	84.6
HSSA	270	49.3	68.5	89.3
F15A	199	56.3	85.9	98.0
F15B	322	10.9	24.5	78.9
FG50	290	54.8	81.4	97.6
X-1	330	56.7	79.1	98.8
X-2	330	53.6	80.6	98.5

WEATHER: HAZE

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	802	34.8	59.7	92.8
HSS2	818	53.3	78.6	97.3
HSSA	748	20.9	55.6	98.1
F15A	544	30.2	46.7	74.5
F15B	810	13.7	26.7	64.4
FG50	748	52.8	78.1	92.4
X-1	810	45.6	70.0	97.0
X-2	816	30.9	63.6	98.0

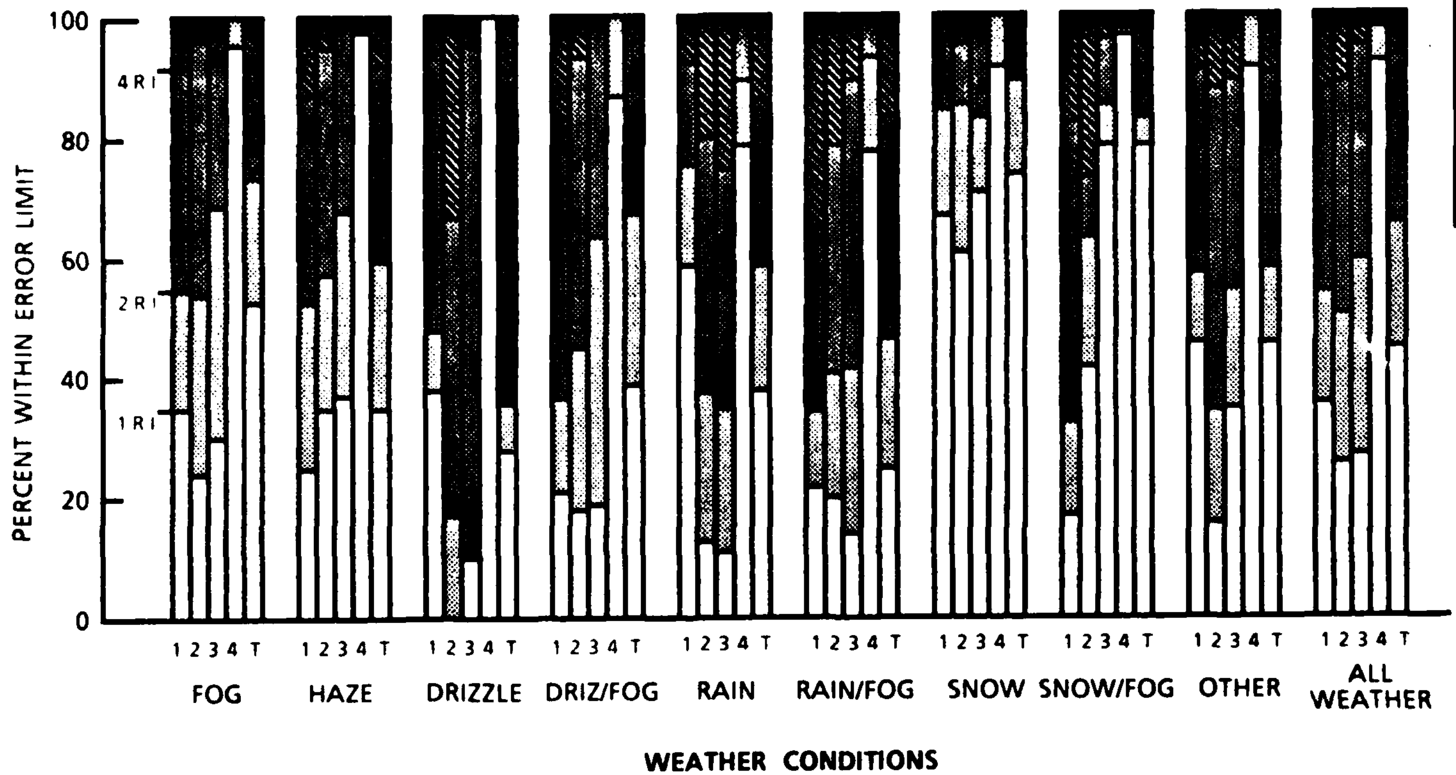
WEATHER: DRIZZLE AND FOG

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	667	39.0	67.9	97.2
HSS2	666	72.2	91.7	98.5
HSSA	552	51.8	76.8	98.2
F15A	603	70.2	81.4	86.6
F15B	602	60.3	74.3	88.9
FG50	436	80.5	95.2	99.9
X-1	667	66.0	83.4	93.6
X-2	667	67.9	88.3	99.6

WEATHER: RAIN AND FOG

Sensor	Tot No	% Within Error of		
		1 R.I.	2 R.I.	4 R.I.
HSS1	1011	25.1	47.1	84.0
HSS2	1033	43.1	67.3	92.7
HSSA	906	28.0	49.9	88.7
F15A	756	64.6	84.0	94.2
F15B	970	21.7	40.7	76.8
FG50	856	56.7	80.6	96.6
X-1	1032	49.5	77.9	96.8
X-2	1032	49.4	77.6	99.2

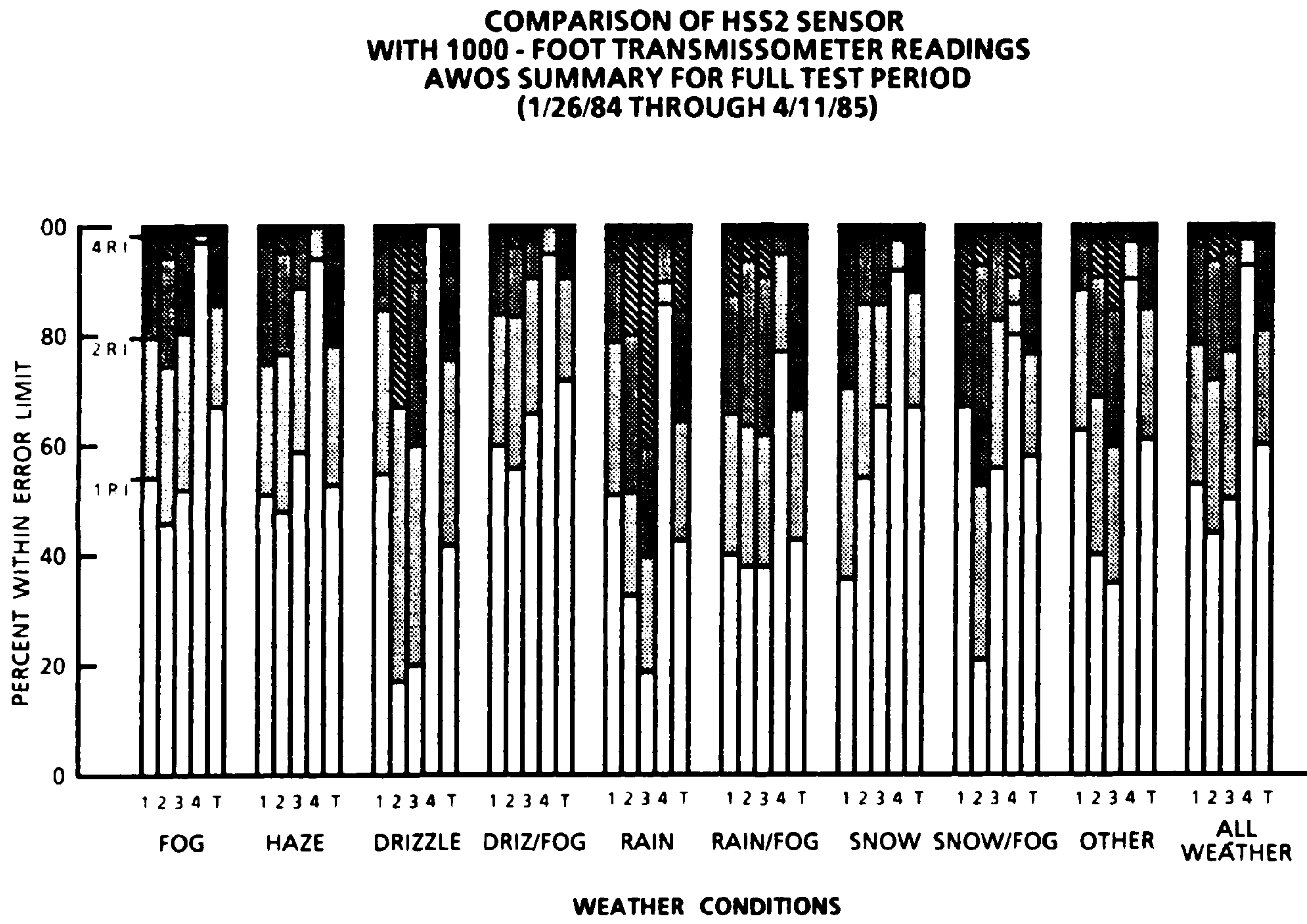
COMPARISON OF HSS1 SENSOR WITH 1000 - FOOT TRANSMISSOMETER READINGS AWOS SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)



KEY

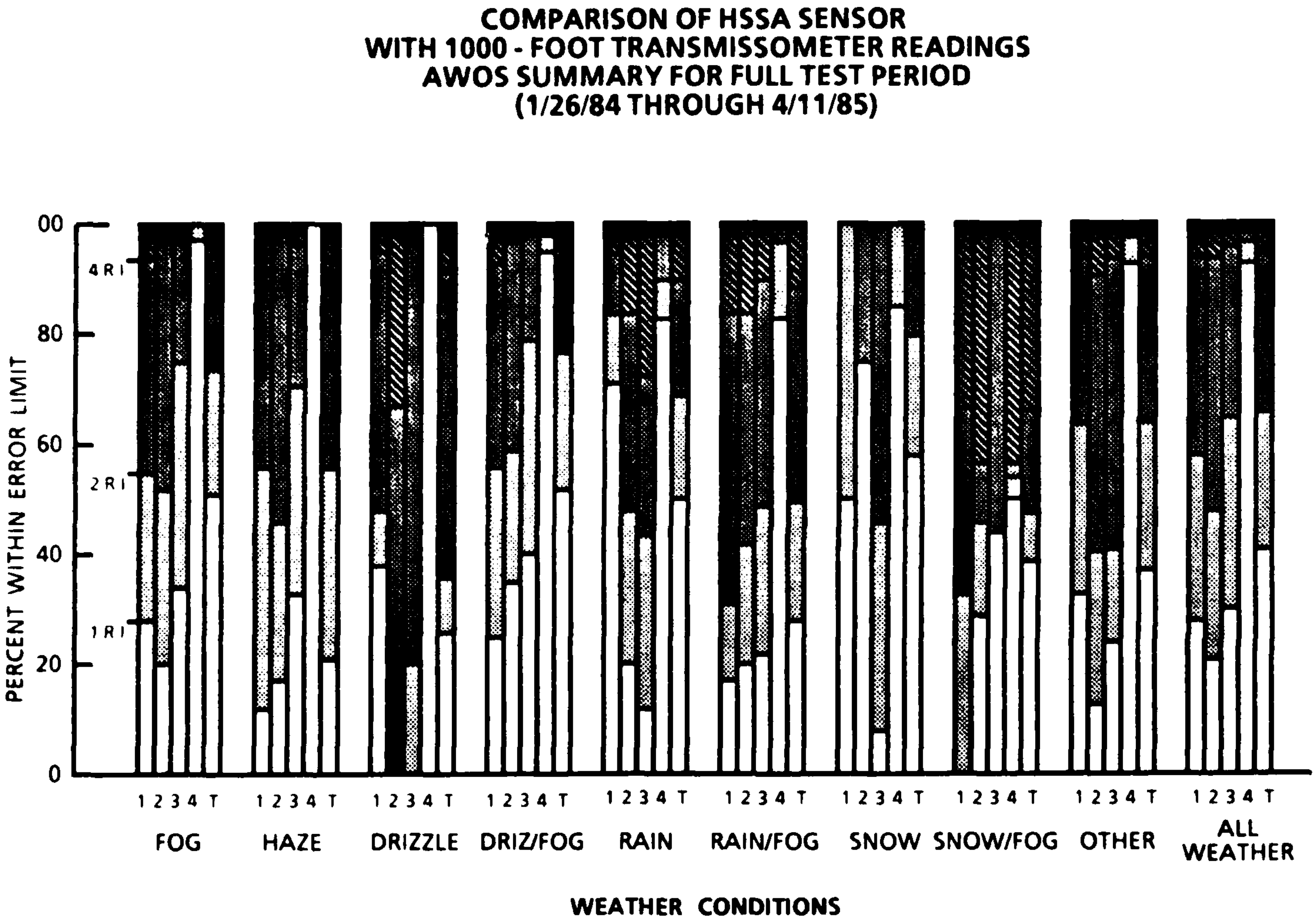
PLOT	SIGMA Km^{-1} (Visibility Miles)
1	0.20 - 0.33 (9.00 - 5.50)
2	0.33 - 0.66 (5.50 - 2.75)
3	0.66 - 1.60 (2.75 - 1.125)
4	1.60 - 9.61 (1.125 - 0.187)
T	0.20 - 9.61 (9.00 - 0.187)

FIGURE 4-11. ERROR RANGE ANALYSIS FOR AWOS RANGE



PLOT	SIGMA Km^{-1} (Visibility Miles)
1	0.20 - 0.33 (9.00 - 5.50)
2	0.33 - 0.66 (5.50 - 2.75)
3	0.66 - 1.60 (2.75 - 1.125)
4	1.60 - 9.61 (1.125 - 0.187)
T	0.20 - 9.61 (9.00 - 0.187)

FIGURE 4-11. ERROR RANGE ANALYSIS FOR AWOS RANGE (Cont.)

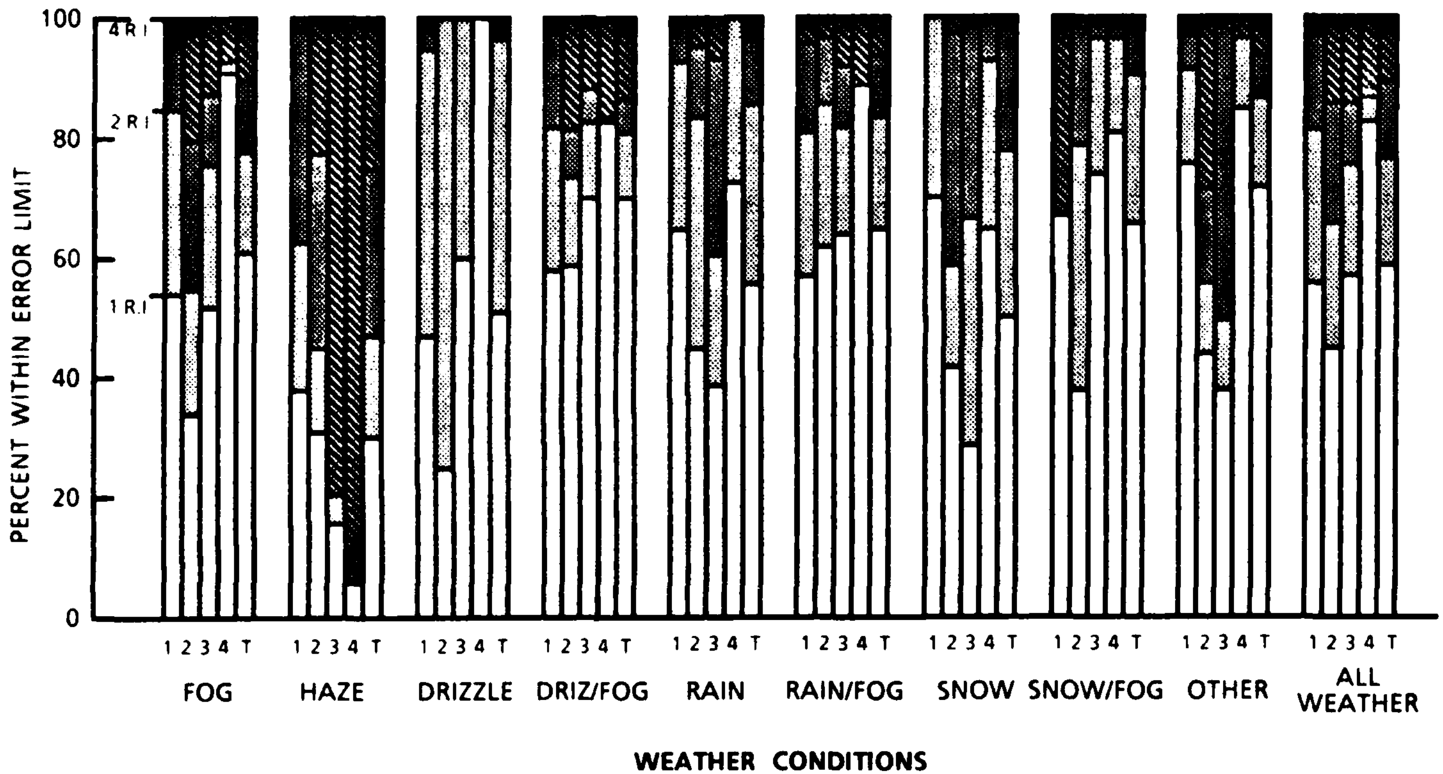


KEY

PLOT	SIGMA Km^{-1} (Visibility Miles)
1	0.20 - 0.33 (9.00 - 5.50)
2	0.33 - 0.66 (5.50 - 2.75)
3	0.66 - 1.60 (2.75 - 1.125)
4	1.60 - 9.61 (1.125 - 0.187)
T	0.20 - 9.61 (9.00 - 0.187)

FIGURE 4 11. ERROR RANGE ANALYSIS FOR AWOS RANGE (Cont.)

COMPARISON OF F15A SENSOR WITH 1000 - FOOT TRANSMISSOMETER READINGS AWOS SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

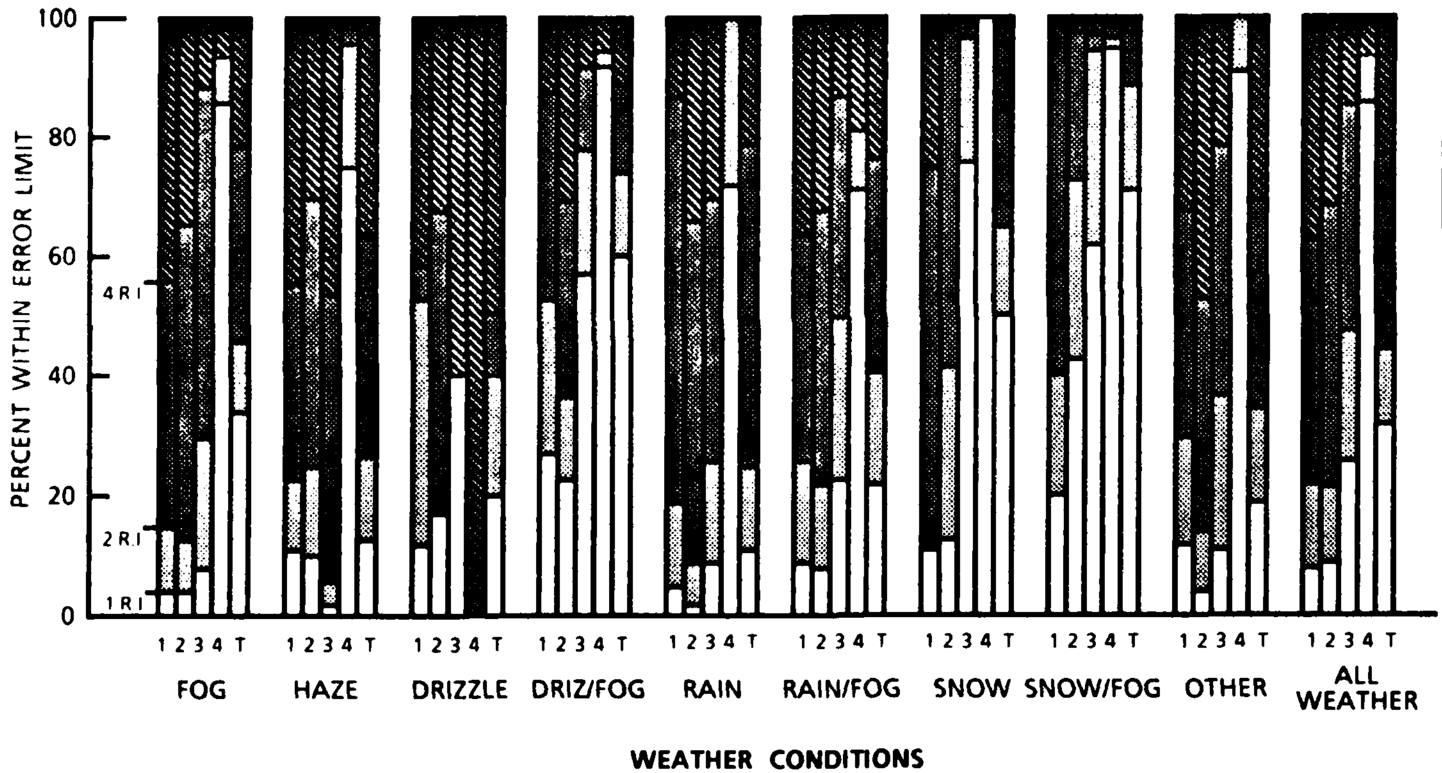


KEY

PLOT	SIGMA Km^{-1} (Visibility Miles)
1	0.20 - 0.33 (9.00 - 5.50)
2	0.33 - 0.66 (5.50 - 2.75)
3	0.66 - 1.60 (2.75 - 1.125)
4	1.60 - 9.61 (1.125 - 0.187)
T	0.20 - 9.61 (9.00 - 0.187)

FIGURE 4-11. ERROR RANGE ANALYSIS FOR AWOS RANGE (Cont.)

COMPARISON OF F15B SENSOR WITH 1000 - FOOT TRANSMISSOMETER READINGS AWOS SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

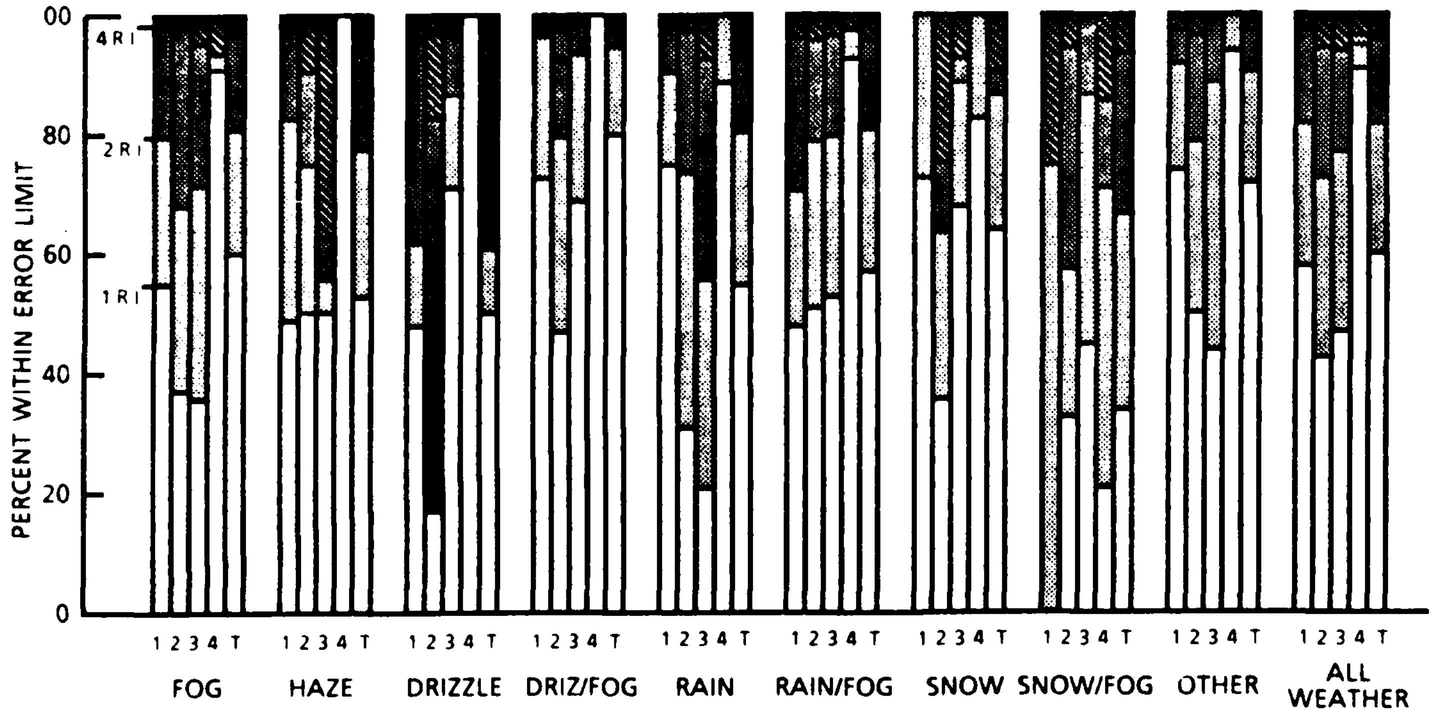


KEY

PLOT	SIGMA Km^{-1} (Visibility Miles)
1	0.20 - 0.33 (9.00 - 5.50)
2	0.33 - 0.66 (5.50 - 2.75)
3	0.66 - 1.60 (2.75 - 1.125)
4	1.60 - 9.61 (1.125 - 0.187)
T	0.20 - 9.61 (9.00 - 0.187)

FIGURE 4-11. ERROR RANGE ANALYSIS FOR AWOS RANGE (Cont.)

COMPARISON OF FG50 SENSOR WITH 1000 - FOOT TRANSMISSOMETER READINGS AWOS SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

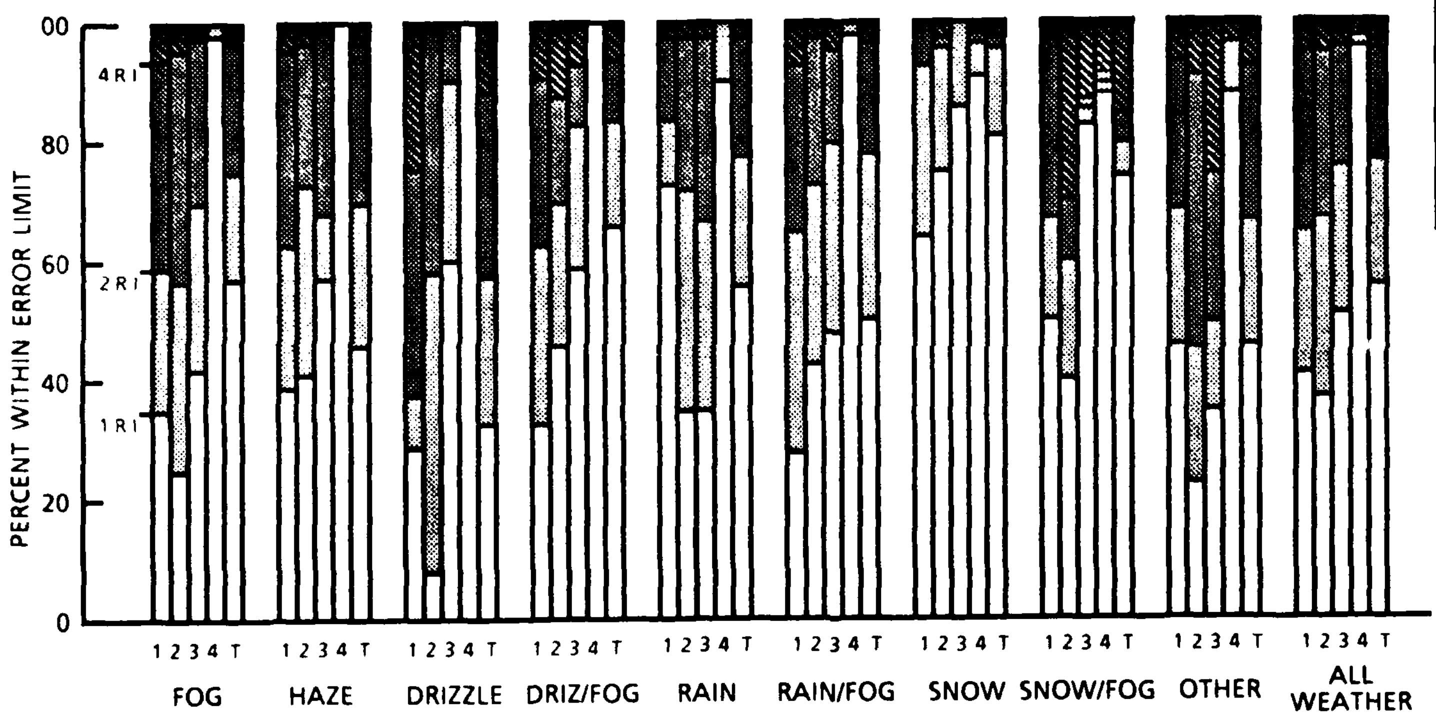


KEY

PLOT	SIGMA Km^{-1} (Visibility Miles)
1	0.20 - 0.33 (9.00 - 5.50)
2	0.33 - 0.66 (5.50 - 2.75)
3	0.66 - 1.60 (2.75 - 1.125)
4	1.60 - 9.61 (1.125 - 0.187)
T	0.20 - 9.61 (9.00 - 0.187)

FIGURE 4-11. ERROR RANGE ANALYSIS FOR AWOS RANGE (Cont.)

COMPARISON OF X-1 SENSOR WITH 1000 - FOOT TRANSMISSOMETER READINGS AWOS SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

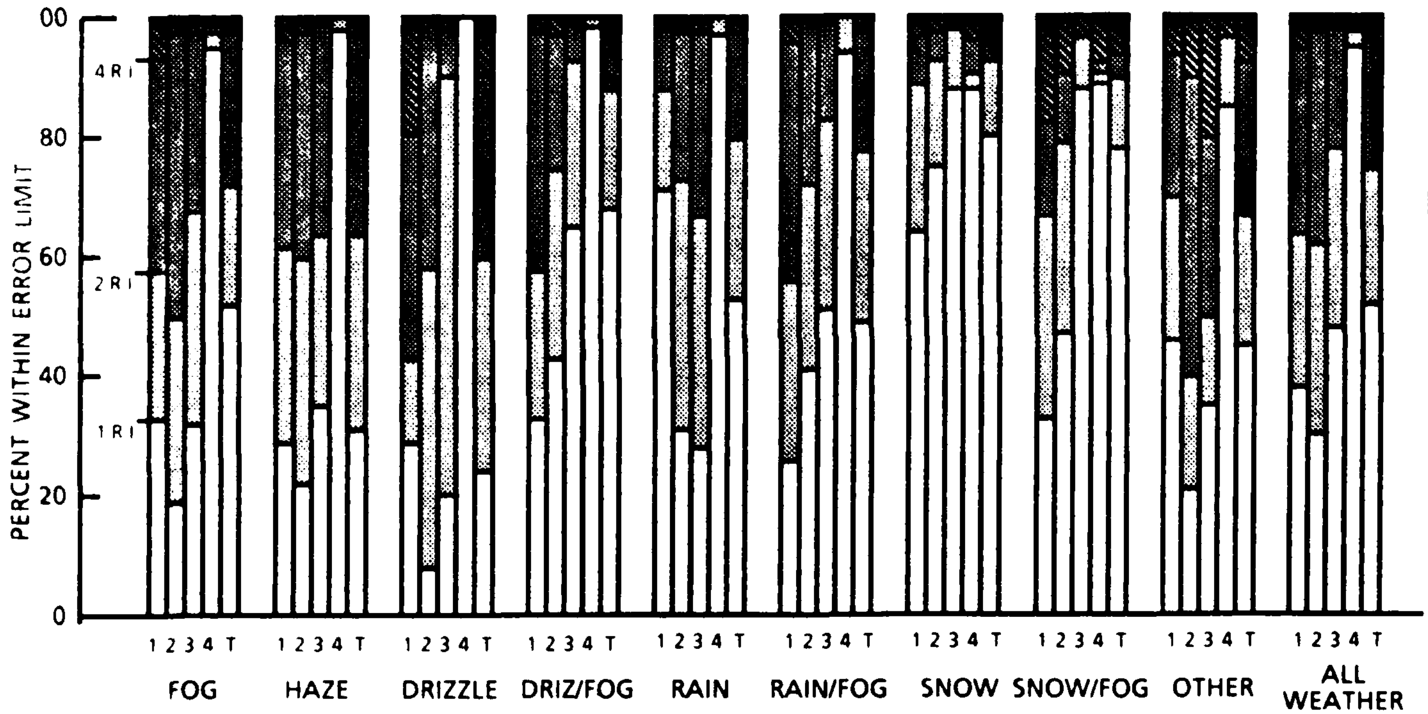


KEY

PLOT	SIGMA Km^{-1} (Visibility Miles)
1	0.20 - 0.33 (9.00 - 5.50)
2	0.33 - 0.66 (5.50 - 2.75)
3	0.66 - 1.60 (2.75 - 1.125)
4	1.60 - 9.61 (1.125 - 0.187)
T	0.20 - 9.61 (9.00 - 0.187)

FIGURE 4-11. ERROR RANGE ANALYSIS FOR AWOS RANGE (Cont.)

COMPARISON OF X-2 SENSOR WITH 1000 - FOOT TRANSMISSOMETER READINGS AWOS SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

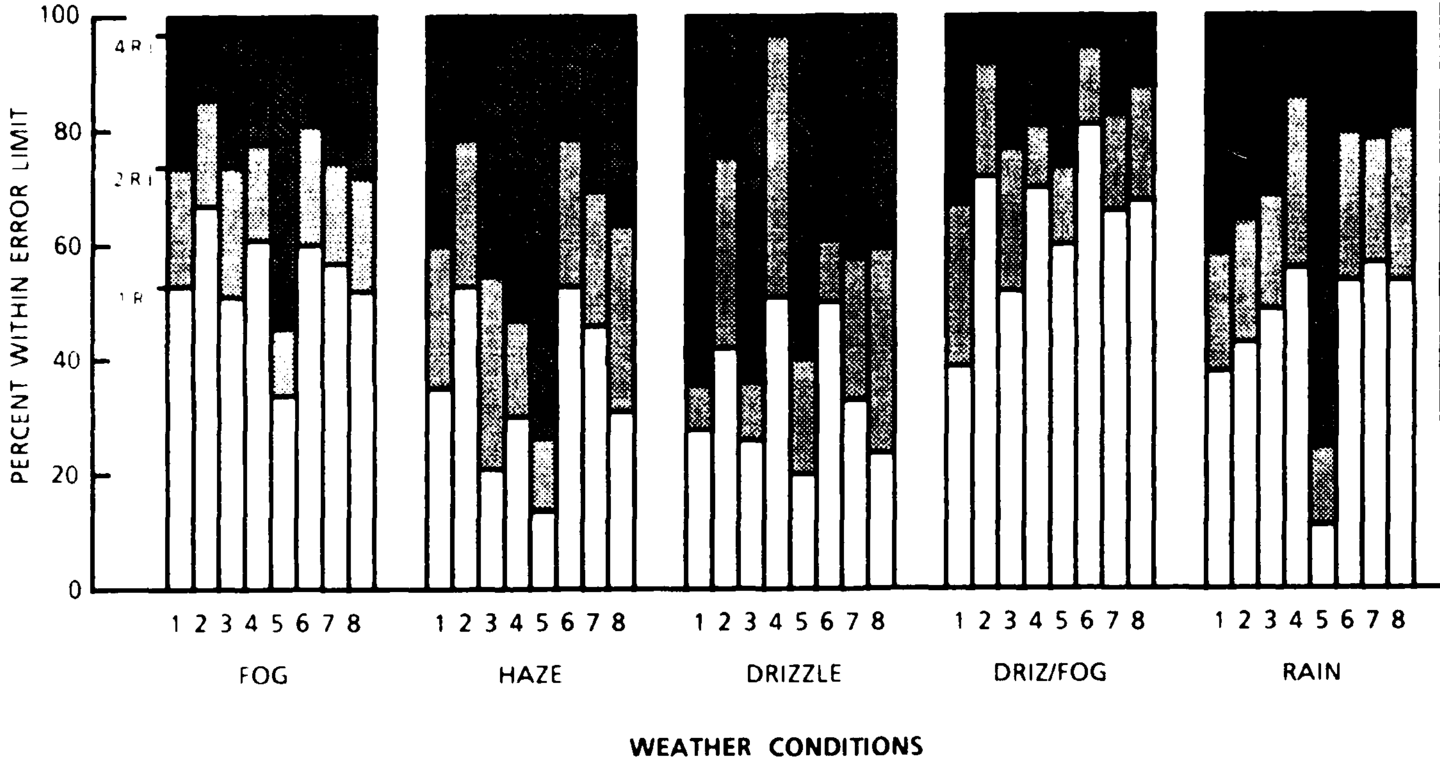


KEY

PLOT	SIGMA Km^{-1} (Visibility Miles)
1	0.20 - 0.33 (9.00 - 5.50)
2	0.33 - 0.66 (5.50 - 2.75)
3	0.66 - 1.60 (2.75 - 1.125)
4	1.60 - 9.61 (1.125 - 0.187)
T	0.20 - 9.61 (9.00 - 0.187)

FIGURE 4-11. ERROR RANGE ANALYSIS FOR AWOS RANGE (Cont.)

COMPARISON OF SENSORS WITH 1000 - FOOT TRANSMISSOMETER READINGS FOR FULL VISIBILITY RANGE (0.2 - 9.0 MILES) AWOS SUMMARY FOR FULL TEST PERIOD (1/26/84 THROUGH 4/11/85)

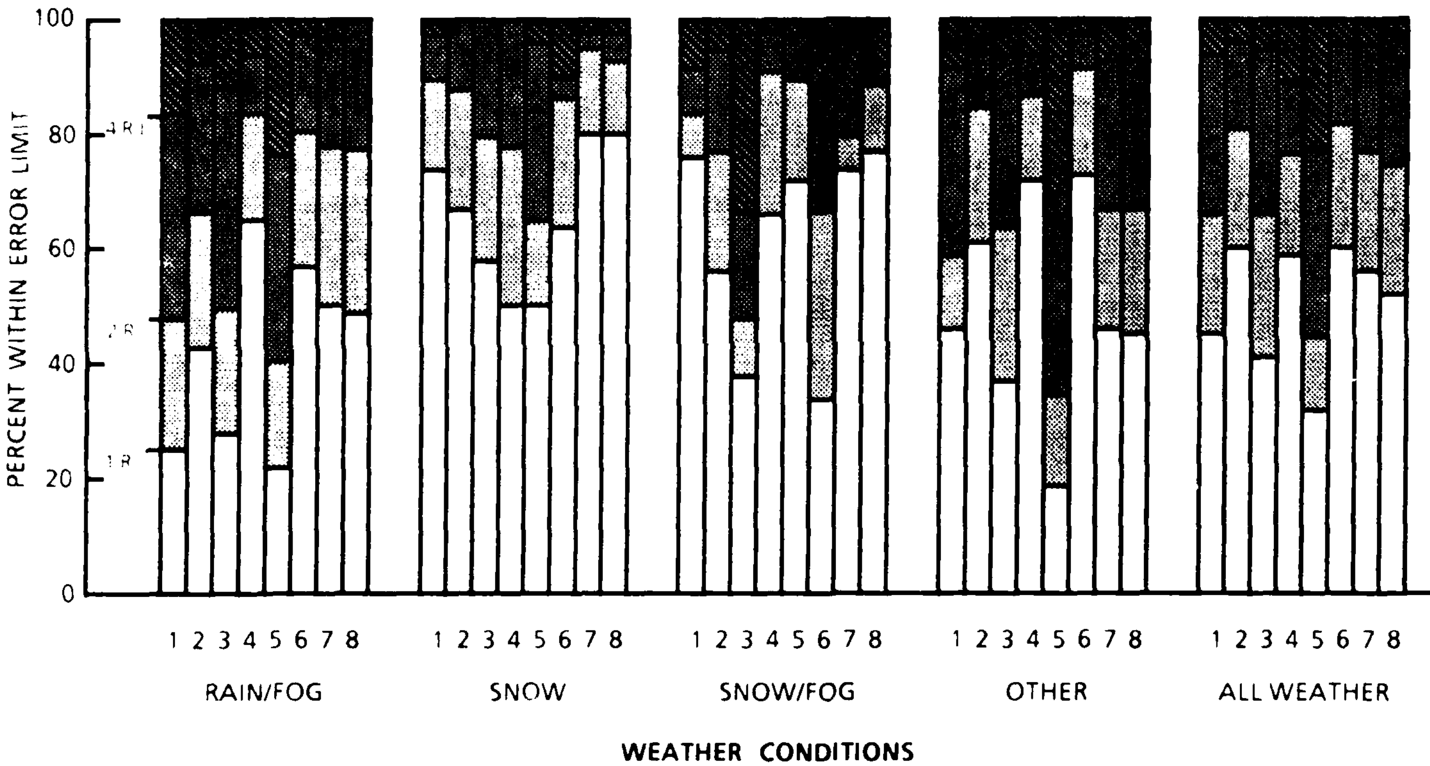


KEY

PLOT	SENSOR
1	HSS1
2	HSS2
3	HSSA
4	F15A
5	F15B
6	FG50
7	X-1
8	X-2

FIGURE 4-12. ERROR RANGE ANALYSIS SUMMED OVER SIGMA, FOR AWOS RANGE

COMPARISON OF SENSORS
WITH 1000 - FOOT TRANSMISSOMETER READINGS
FOR FULL VISIBILITY RANGE (0.2 - 9.0 MILES)
AWOS SUMMARY FOR FULL TEST PERIOD
(1/26/84 THROUGH 4/11/85)



KEY

PLOT	SENSOR
1	HSS1
2	HSS2
3	HSSA
4	F15A
5	F15B
6	FG50
7	X-1
8	X-2

FIGURE 4-12. ERROR RANGE ANALYSIS SUMMED OVER SIGMA (Cont.)

4.7 Large Sensor Disagreements

The foregoing analysis showed a surprisingly high percentage of the data to lie in the largest error ranges, >100 percent variation from the standard transmissometer for the RVR range, or >4 Reporting Increments for the AWOS range. To investigate this further, the >2X error cases for the RVR range of the X-1, X-2, HSS1, HSS2 and HSSA sensors were studied. These were all cases in which the 300-foot and 500-foot transmissometers agreed to within 10 percent, but the FSM reading was less than half or more than twice the average of the two transmissometer readings.

The breakdown of these hours by time periods and sigma ranges is shown in Tables O-1 in Appendix O. Table 4-21 summarizes the percentage of the data which was in the >2X range for each of the five sensors, and the percentage of these hours that occurred during pure snow or snow and fog weather conditions. For the EG&G sensors, the majority of these discrepancies were under snowy conditions. These sensors have been known to respond poorly in snow. However, it is evident that the HSS sensors, and even the transmissometers, are subject to errors in this type of weather. Figure O-1 is a strip chart covering a period during one of these storms involving blowing snow, showing the effect of the buildup of snow and ice in the sensors. The FG50 sensor was inoperative during the entire period. Figures O-2 show scatter plots covering a period near the start of this storm, when some of the sensors had been affected. Figures O-3 show further deterioration in the sensor responses several hours later.

Although the HSS sensors were affected by snowy conditions, more occurrences of >2X error corresponded to conditions of rain, fog, or rain & fog. These weather conditions account for 61.4, 60.3 and 57.7 percent of the >2X error hours for the HSS1,

TABLE 4-21. LARGE DISCREPANCIES IN SENSOR DATA

Sensor	Total Number of Data Hours*	Error > 2X Number of Hours	Error > 2X Percent of Total Hours	Snow or Snow & Fog Number of Hours	Snow or Snow & Fog Percent of Error Hours
X-1	260	22,436	1.16	225	86.5
X-2	363	23,393	1.62	215	59.2
HSS1	490	22,294	2.20	129	26.3
HSS2	907	22,522	4.03	215	23.9
HSSA	589	18,859	3.12	211	35.8

*Transmissometers agree within ± 10%

HSS2 and HSSA sensors, respectively. Scatter plots were made for representative periods which contained large groups of hours in the high error range.

One of the representative incidents is shown in the strip chart of Figure O-4 (see Appendix O) and the scatter plots of Figures O-5. Note that sensors F15A and FG50 are inoperative throughout the incident and that the Y sensor, which clearly reads too high at the start of the strip chart, appears to settle back and behave properly thereafter. The HSSA sensor appears to have undergone a shift in calibration and reads high throughout the incident. Many of the occurrences of high error range for the HSS sensors are of this type, an unexplained calibration change which is not sufficient to show clear signs of failure.

A third type of incident which resulted in large error readings is due to failure to recognize when a sensor was not operating properly, and hence not including it in the failure file, which would have dropped the point from the statistics. An example is the failure of the X-1 sensor shown in the strip chart of Figure O-6 and the scatter plots of Figures O-7 (see Appendix O). In this particular case, the sensor was replaced about two weeks after this incident.

Another type of incident which appears to cause some of the large discrepancies in the ratio between the FSMs and the transmissometer was due to saturation of the transmissometer. This occurred under what was apparently locally heavy fog conditions, although the weather service reported no lower than three miles visibility. Saturation of the transmissometers was not considered a failure to be reported in the failure file. However, the FSMs are generally able to remain linear under much more dense conditions than the transmissometer, hence the ratios show large FSM/transmissometer values. The incident shown in the strip chart of Figure O-8 (see Appendix O) is a good example, showing clear saturation of the T000 (1000-foot baseline) and T500 transmissometers, and a period when the T300 and the EG&G sensors also appear to be saturated. Data should have been excluded from the statistics by the SENSOR program when the T500 was saturated and the T300 was not. The HSS2, F15A and FG50 are inoperative during the period. The scatter plots of Figures O-9 clearly show the T500 saturation.

In summary, most of the occurrences of >100 percent difference between an FSM sensor and the 500-foot transmissometer fall into one of the following categories:

(1) Snowy conditions, where none of the sensors behave well;

(2) Saturation of the transmissometer, which should have been excluded in the SENSOR program;

(3) A failed sensor which was not identified as such; or

(4) Unexpected calibration shifts in a sensor, which either correct themselves or lead towards failure of the instrument.

5. SUMMARY

5.1 Philosophy

The science of visibility has a long history because of the very complex issues involved. The perceived visibility depends upon four independent factors:

1. The object being viewed,

2. The observer,

3. The atmosphere, and

4. The lighting.

Because of these many variables, the visibility is not precisely defined. Measurements of visibility are made by making reasonable assessments of the four factors. Visibility sensors deal only with the third item, the atmosphere, which is characterized by a single parameter, the extinction coefficient. The other variables are handled by using standard equations based on visibility research. For example, runway visual range (RVR) is specified by the human detection thresholds for lights and contrast (factor 2), the runway light setting (factor 1) and the background luminance level (day or night) (factor 4). The extinction coefficient measured by a single sensor is used to characterize the atmosphere within about 2000 feet of the sensor.

The accuracy of a visibility measurement in predicting what an observer will experience thus depends upon the following variables:

1. Spatial variations in the extinction coefficient.

2. Variations in the observer.

3. Errors in defining the lighting.

4. Errors of the visibility sensor.

In this context, the accuracy required for a visibility sensor need be only enough that sensor errors not accentuate the errors from other sources. For example, a typical rms spatial variation for fog at 2000 feet separation is about ±30 percent (see Appendix P). It is important not to confuse the reporting precision of a visibility measurement with the required accuracy. The customary reporting resolution for visibility is often much finer than warranted by either the precision of the visibility estimate or the accuracy of existing sensors.

The evaluation of visibility sensors is plagued by an issue closely related to the imprecision in the definition of visibility. What can be used as a visibility standard? Human observations are too variable to be used as a standard. Reference 1 showed a ±50 percent variation in comparisons of visibility sensors to human observations. Much closer agreement is usually shown in comparisons between different visibility sensors. The selection of Tasker RVR 500 transmissometers as the standard sensors for the current study was somewhat arbitrary, but was based on the following criteria:

1. A transmissometer is self calibrating.

2. The Tasker Model RVR 500 is the current U.S. visibility sensor.

There are two considerations that limit the usefulness of this standard. First, the light spectrum used in the RVR 500 includes a considerable amount of infrared light. When the RVR 500 is compared with transmissometers from other countries, which use different light sources, significant differences are noted. A Japanese transmissometer that uses infrared light emitting diodes gives extinction coefficients about 23 percent lower. On the other hand, a German transmissometer using a Xenon flashlamp gives extinction coefficients about 12 percent higher. Although the German transmissometer uses a light spectrum closer to the response of the human eye, all three instruments are accepted as valid visibility instruments in their own countries. It is evident that the observed variations in transmissometer response are within the acceptable range for aviation visibility measurements.

The second difficulty in using the RVR 500 as a standard is the difficulty in getting two transmissometers to agree, as discussed in Section 4.4. Much of the disagreement is due to spatial variations in the extinction coefficient. In addition, the 300- and 500-foot transmissometers show a consistent systematic disagreement of about 8 percent. In light of the observed disagreements between two transmissometers, it is not surprising that perfect agreement is not obtained between a transmissometer and a forward scatter meter.

5.2 Sensor Performance

A total of 60 incidents of low visibility were chosen by investigating both the weather information from the site and strip charts of extinction coefficients as a function of time. The incidents included various types of weather conditions, but most of them contained at least some fog, which was the weather condition most responsible for reduced visibility. Complete

strip charts were run for all 60 incidents, and scatter plots were produced to compare the response of each of the sensors to a standard transmissometer. The time variations in the slopes of the scatter plots were investigated, both on a short term and on a long term basis, in Sections 4.2 and 4.3 respectively. The scatter in the slopes was more extensive than expected, but most of the outlying points were explained in terms of instrument failure or differences in the type of fog. No evidence of calibration drift was obtained from these plots.

A comprehensive statistical analysis of the data was performed with the program SENSOR. As a first step, the program identified all cases where the 300-foot and 500-foot baseline transmissometers disagreed by at least 10 percent. These cases are properly excluded from the statistical analysis, since most of them signify spatial variations in the atmospheric conditions sufficient that the forward scatter meter would not be expected to measure the same conditions as the transmissometer. As indicated in Section 4.4, a significant fraction of the data was excluded in this manner.

For each sensor, the SENSOR program produced tables of sigma values as a function of time, weather conditions, and sigma range. To provide for more convenient comparison of the effectiveness of the sensors, the analysis of Sections 4.5 and 4.6 integrated out each of the variables in turn. First, only the overall sigma range was considered, so that the sigma values for each sensor were a function of time and weather conditions. Next, only the full test period was considered, so that the sigma values for each sensor were presented as a function of the weather conditions only. Finally, the all-weather table provides convenient figures-of-merit for comparison of the sensors.

Data is presented for the RVR range in terms of the ratio of sensor sigma to transmissometer sigma. Nine ratio groups were identified, with ratios of $<$ 0.5, 0.5-0.75, 0.75-0.8, 0.8-0.835, 0.835-1.165, 1.165-1.25, 1.25-1.35, 1.35-2.0, and $>$ 2.0, and numbered 1 through 9 respectively. The middle group contains all data where the FSM and transmissometer agree within 16.5 percent. One figure-of-merit is the average group number, obtained by weighting each group number with the number of cases in the group. The results are shown in Table 5-1.

Comparison of the number of cases for each sensor is a good indicator of the fraction of the test period that the sensor was in operation. The best sensor from Table 5-1 is the FG50, followed by the HSS2 and X-1 sensors, however, the FG50 was out of operation for a considerable period. This analysis can be misleading, however, because a "perfect" 5.0 can be obtained by half of the readings in group 1 and half in group 9, as well as all of the readings in group 5. The final comparison took this into account by considering percentage discrepancies between the FSM and transmissometer for the RVR range, and the number of reporting increments (see below) difference for the AWOS range. These results, for all-weather conditions, are presented in Figure 5-1 and 5-2 for the RVR and AWOS ranges respectively.

The all-weather data comparison is most convenient for assessing comparative sensor performance. On Figure 5-1 and 5-2, the best performance is indicated by the maximum percentage within the lower unshaded section and the minimum percentage within the upper unshaded area. For the RVR range, on Figure 5-1, the EG&G sensor labeled X-1 performed best from both points of view. It had the smallest percent of factor-of-two errors (1.2%) and the greatest percent with less than 16.5 percent error (72.4%). The next best performers considering the factor-of-two errors were

TABLE 5-1. AVERAGE GROUP NUMBERS FOR RVR RANGE

Sensor Name	Number of Cases	Average Group Number
HSS1	22,294	5.72
HSS2	22,522	5.11
HSSA	18,858	5.30
F15A	13,235	4.15
F15B	22,021	5.66
FG50	18,343	5.07
X-1	22,436	5.12
X-2	22,393	5.42

the X-2 and HSS1 sensors, with 1.7 percent and 2.3 percent, respectively. On the other hand, the FG50, F15A and X-2 sensors had the next best percentages of data in group 5, with 63.3 percent, 62.9 percent and 61.4 percent, respectively.

For the AWOS sensors, data was reported in terms of the number of reporting increments by which the FSM and transmissometer disagreed. Reporting increments, which are more fully explained in Table 3-3, are a series of 18 visibility ranges in miles, denoted by the labels $<$ 0.25, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0, 8.0, and $>$8.0 miles. For the AWOS range, on Figure 5-2, the X-2 sensor has the minimum percentage of data with more than four reporting increment error, 2.0 percent, followed by the HSS2, FG50 and X-1 sensors, with 3.7 percent, 3.8 percent and 3.9 percent respectively. The FG50 sensor has the maximum percentage of data within one reporting increment, 60.1 percent, followed by the HSS2 and F15A sensors with 59.5 percent and 58.6 percent respectively.

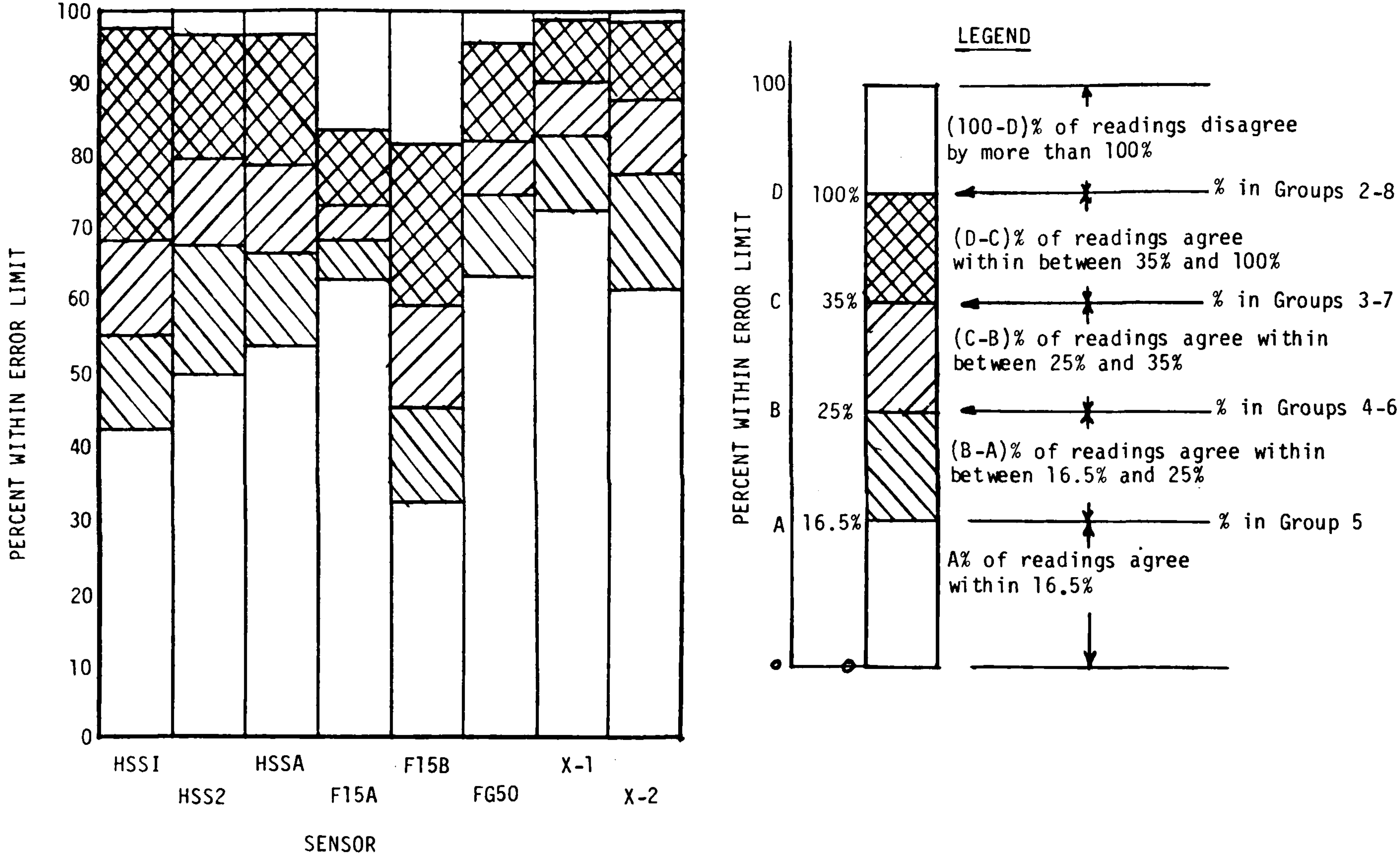


FIGURE 5-1. RVR RANGE COMPARISON OF SENSORS (ALL WEATHER CONDITIONS)

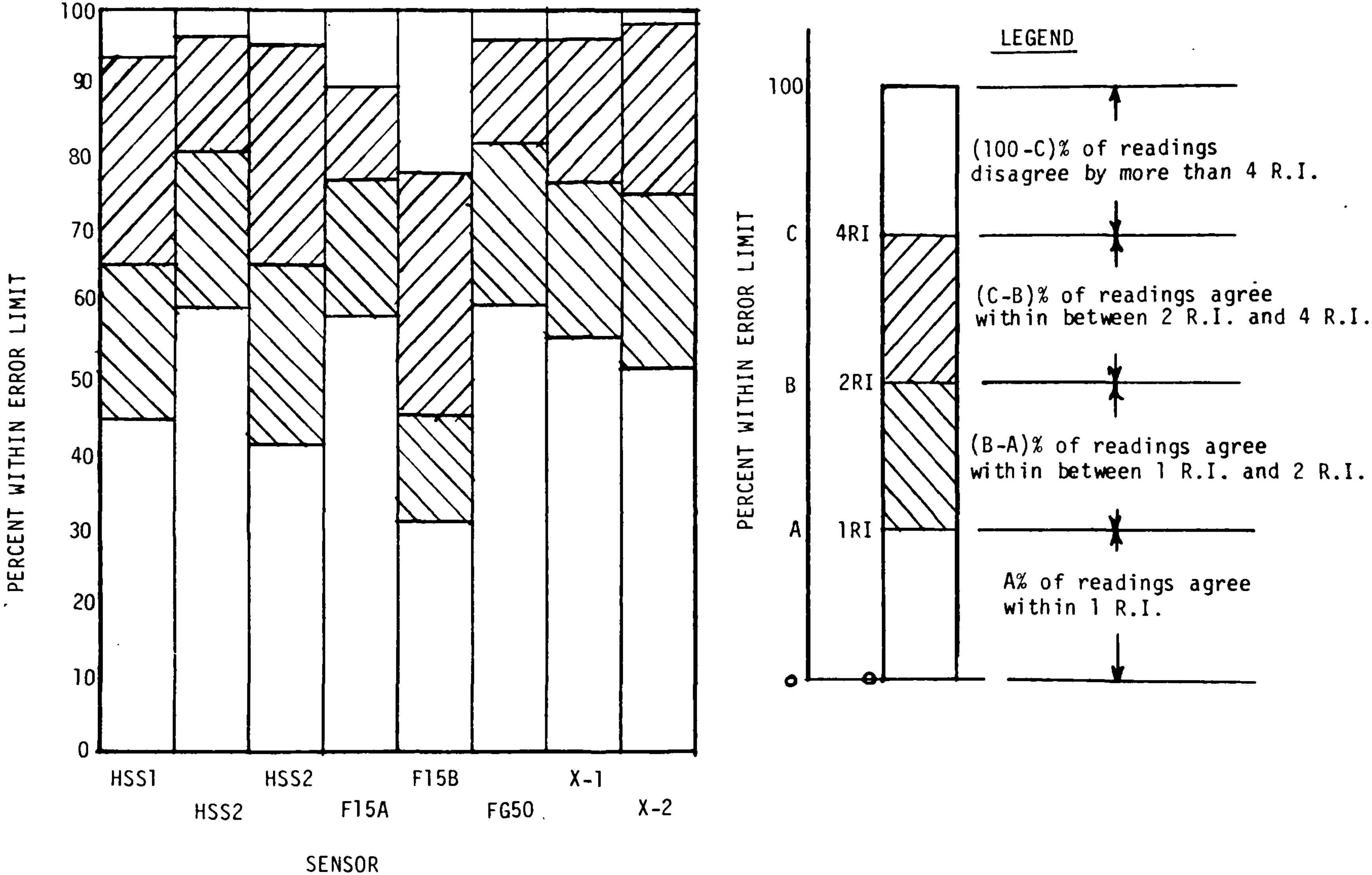


FIGURE 5-2. AWOS RANGE COMPARISON OF SENSORS (ALL WEATHER CONDITIONS)

5.3 Conclusions

Data was collected at Otis ANGB on the USAF/AFGL sensors during the period between 1/5/84 and 5/2/85. With several missing weeks of data, there was a total of 60 weeks of data used in this analysis. The following general observations can be made:

1. Most of the episodes showed variations of less than 15 percent in the slope of the scatter plots of forward scatter meter versus the T500 transmissometer. Of those events showing greater than 15 percent slope variations for the two EG&G sensors under fog conditions, half could be explained by inhomogeneous fog or sensor failure. Most of the rest had low extinction coefficients, where the overall slope was influenced by the higher "haze" slope of the forward scatter meter. Finally, two of the slope variations (both less than 20%) had no explanation other than a dependence on the type of fog or a temporary calibration shift. Thus forward scatter meters can give a consistent response to fog with maximum variations of no more than 20 percent.

2. Study of the agreement among two crossed transmissometers showed that a surprisingly large fraction of the readings did not agree within 10 percent, despite the fact that the transmissometers underwent normal maintenance and were recalibrated daily using FSM data. Only 68 percent of the data was in agreement on an overall basis (all sigmas and weather conditions) for the RVR range. This was reduced to 45 percent agreement for the AWOS range. It is considered unlikely that this is a true

measure of the variability of the atmosphere over the test site, since transmissometer errors appear to be making a significant contribution.

3. Statistics of the comparison of sigmas from each of the sensors compared to the standard transmissometer showed a large dependence upon the weather conditions and the extinction coefficient range. Most of the results did lie within the 16.5 percent (RVR) or one reporting increment (AWOS) limits. The best sensor, the EG&G X-1 sensor, showed 72 percent of the RVR measurements within $\pm$16.5 percent agreement. A surprisingly large number of measurements exceeded the 100 percent or four reporting increment limits. These serious errors were mostly caused by undetected sensor failures, including such problems as being clogged with snow.

4. The best forward scatter meter appears to do a reasonable job of monitoring the visibility variations of the atmosphere. One proposed acceptance criterion required that 90 percent of the RVR measurements agree with a transmissometer to within $\pm$16.5 percent. This level of agreement was not achieved. In view of the limited agreement of two transmissometers operating under the same conditions, it could be argued that this criterion expected too much from the FSMs. That the extinction coefficients derived from the scatter meters do not always agree with those from the transmissometers does not rule out their use in this regard. Agreement is definitely better as the visibility is reduced, which indicates that the FSMs work best when they are most needed. Perhaps a more meaningful way to show FSM acceptability would be to deter-

mine how often decisions regarding landing conditions would be different using the FSM rather than the transmissometer.

5. Although the EG&G Model 207 visibility sensor gave the best performance in this evaluation, it cannot be considered for operational deployment because of its unreliability. Moreover, it is no longer in production. The large scattering volume of the EG&G Model 207 appears to contribute to the stability of its response. The HSS sensors, which are much more reliable because they have no moving parts or incandescent light bulbs, have a small scattering volume and give more erratic measurements. Perhaps the ideal sensor would be of the HSS type with a larger scattering volume.

6. REFERENCES

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2. Spitzer, E.A. and McWilliams, I.G. "Evaluation of Visibility Sensors at Otis Air National Guard Base," Report No. DOT-TSC-FA515-PM-85-20, June 1985, DOT/TSC, Cambridge, Mass.

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